BICYCLIST PERCEIVED LEVEL OF TRAFFIC STRESS: A QUALITY OF SERVICE MEASURE

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**BICYCLIST PERCEIVED LEVEL OF TRAFFIC STRESS:
A QUALITY OF SERVICE MEASURE**

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DEDICATION

In memory of my grandfather, Richard Carter;

my nephew, Liam Carter; and my uncle, John Tullis.

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
ABC	Advance, Basic, or Children
AASHTO	American Association of State Highway and Transportation Officials
ARC	Atlanta Regional Commission
BCI	Bicycle Compatibility Index
BEQI	Bicycle Environmental Quality Index
BLOS	Bicycle Level of Service
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
HCM	Highway Capacity Manual
LOS	Level of Service
LTS	Level of Traffic Stress
MTI	Mineta Transportation Institute
MUTCD	Manual on Uniform Traffic Control Devices
NACTO	National Association of City Transportation Officials
USDOT	United States Department of Transportation

SUMMARY

Levels of cycling in the US remain low compared to its international peers. Building well connected bicycle facilities which appeal to the majority of the public has the potential to increase bicycling mode share. Research has shown that Americans have different tolerances for perceived traffic stress. While some people can tolerate higher traffic volume and motor vehicle speed, most current and potential bicyclists prefer low traffic volume and motor vehicle speeds. The objective of this study is to refine and apply a bicycle quality of service tool which will allow the assessment of transportation infrastructure design based on users' perceived stress also known as Level of Traffic Stress (LTS).

This study builds upon, one measure of cyclist comfort, the Mineta Transportation Institute's Level of Traffic Stress tool, by reviewing the literature to modify the traffic and roadway characteristics by which roadways, bikeways, and intersections are classified into four levels of traffic stress. The LTS criteria which are applied to roadways, bikeways, and intersections corresponds to four types of bicyclists, which were also used in the Georgia Institute of Technology Cycle Atlanta app. LTS 1 Interested, but Concerned (I have heard a lot about cycling and I am curious to try it, but I require facilities geared to cyclists before I would do so); LTS 2 Comfortable, but Cautious (I am comfortable on most roads, but strongly prefer facilities geared to cyclists and will chose another mode depending on facilities); LTS 3 Enthused and Confident (I am confident sharing the road with vehicles but prefer facilities geared to cyclists); LTS 4 Strong and Fearless (I am willing to bike in any situation and being a cyclist is part of my identity).

The LTS quality of service tool was applied to a case study area, a six mile buffer around the Atlanta BeltLine Eastside Trail in Atlanta, Georgia. While an overview of the study area reveals a large amount of LTS 1 and 2 roadways and bikeways further analysis of the Eastside Trail's Bikeshed reveals that the facilities are not well connected. This means that for people

who identify at LTS 1 and LTS 2, estimated to be a majority of current and potential bicyclists, the bike network is disconnected. Unlike other quality of service tools, LTS determines the stress of a route by the link or intersection with the highest link, not by the average stress.

The LTS 1 and LTS 2 bikeshed with and without unsignalized intersection crossing criteria was compared. The manual application of the unsignalized crossing criteria revealed that unsignalized intersection crossing criteria is important to include in network and route analysis. The thesis recommends that future research develop a program to automatically run the unsignalized intersection crossing criteria. Major roadways as cross streets at unsignalized intersections were found to be the main barrier for the low-stress bikeshed. Further analysis of high stress barriers can help reveal locations were strategic bicycle facility investments should be made to increase the connected bicycle network.

CHAPTER 1

INTRODUCTION

1.1 Objective

The objective of this study is to refine and apply a bicycle quality of service tool which will allow the assessment of transportation infrastructure design based on users' perceived stress also known as Level of Traffic Stress (LTS). The LTS quality of service tool was introduced in "Low-Stress Bicycling and Network Connectivity" by Mekuria, Furth, and Nixon [1]. Such a tool is designed to highlight the sections of the network that are perceived as too stressful for the majority of current and potential bicyclists and may be causing gaps that reduce the connectivity of the bicycle network. The aim of the LTS tool is to assist planners and engineers in creating a well-connected bicycle network which will increase bicycle mode share by accommodating the stress tolerance of the majority of the population. In particular, the LTS tool aims to increase the mode share of bicycling by accommodating the preferences of potential bicyclists, especially underrepresented subgroups such as women, families, and the older population.

This thesis focuses on understanding the facility designs and traffic conditions that create a bicycle network that people who do not currently bike, but are interested in biking would be comfortable riding on. The bicycle network includes not only facilities with bicycle specific accommodations, but also any roadway that does not prohibit bicycling by statute or regulation.

Unlike motor vehicle quality of service measures like Level of Service (LOS), the main goal of bicycle quality of service measures should be to increase the mode share of bicycling. Transportation professionals deal with issues of congestion and mobility with motor vehicles and so the focus of level of service tools like the Highway Capacity Manual (HCM) LOS is on mobility or speed [2]. However, if the focus of transportation professionals is on increasing the mode share of bicyclists in the U.S., the bicycle quality of service tools should measure if facilities meet the preferences of current and potential bicyclists. Facilities with adequate perceived comfort are important for potential bicyclists to become current bicyclists and for current bicyclists to bicycle more frequently.

There is a need to develop bicycle quality of service tools, which accommodate the needs of a majority of current and potential riders. Such tools can help prioritize funding of facilities that will increase the connectivity of the bicycle network. For such quality of service tools to be developed, it must first be understood what types of bicyclists there are in the general population, both current and potential riders, including what design criteria they prefer.

A typology should be developed to categorize bicyclists based on distinctive characteristics and the proportion of the population should be determined for each type of bicyclist. Currently, the most widely used typology categorizes bicyclists based on skill level as Advanced, Basic, or Children also known as the ABC typology [3]. However, this typology only categorizes current bicyclists. Geller proposed four types of cyclists, which accommodate the entire population, with Interested but Concerned estimated to be the majority of the population in Portland, OR [4]. Additional research by Dill and McNeil has validated this typology for the Portland area [5]. This typology has gained popularity throughout the United States, yet, further validation of the characteristics of the four types of cyclists and their proportion of the population should occur in cities throughout the United States. Misra et al. refined Geller's four types of bicyclists by dividing the Interested, but Concerned type into two groups: Comfortable, but Cautious and Interested, but Concerned. The Comfortable, but Cautious type was hypothesized to include female bicyclists and/or older bicyclists who are bicycle enthusiasts, but may be more risk adverse [6].

Once a bicyclist typology is defined, then the facility and traffic characteristics that each type prefers can be determined so that facilities can be analyzed using a quality of service tool. Bicycle Level of Service (BLOS) is the most widely accepted quality of service tool in the U.S.

and is featured in the 2010 Highway Capacity Manual [7]. However, research has criticized the HCM BLOS for not being able to assess innovative bicycle facilities like protected cycle tracks, for focusing primarily on arterial roadways, and for counterintuitive reactions to some inputs [8] [9]. Mekuria et al. have worked to develop a quality of service tool which categorizes facilities by LTS [1]. This tool analyzes the quality of service of the bicycle network by applying criteria adopted by the Dutch CROW Design Manual for Bicycle Traffic, such as number of travel lanes, speed limit, and other criteria to determine if a segment or intersection exceeds the acceptable perceived stress level. Mekuria et al. equate the facility design preferences of the Interested but Concerned type with the target user of the Dutch CROW Design Manual for Bicycle Traffic [1]. This tool holds great potential to meet latent bicycle demand, however, significant research needs to be conducted to validate the four types of cyclists typology and the design and traffic criteria which are used to calculate LTS quality of service.

1.2 Outline

This thesis proceeds as follows; Chapter 2 is a review of the literature on bicyclist typology, variables that influence the choice to bicycle, and models that estimate bicyclist perception of the quality of service of facilities. Chapter 3 discusses the bicyclist typology, Cycle Atlanta LTS, which is the basis for the quality of service tool used in this thesis. The extent of the bicycle network and facility types are also defined. The quality of service tool used in this thesis, LTS, is discussed and the traffic and roadway characteristics which make up the LTS criteria matrices for conventional bicycle lanes with and without on street parking, buffered bike lanes with and without on street parking, shared travel lanes, through movement of bicyclist with right turn only motor vehicle lane, and left-turning bicyclist at a signalized intersection are described in detail with support from related literature. Chapter 5 focuses on the application of the LTS tool in the case study area, a six-mile buffer around the Atlanta Eastside BeltLine in Atlanta, GA. Chapter 6 discusses future research and conclusions for the report.

CHAPTER 2

RESEARCH BACKGROUND/LITERATURE REVIEW

This thesis focuses on building upon the Mineta Transportation Institute (MTI) Level of Traffic Stress (LTS) tool by refining the traffic, roadway, and bikeway characteristics (e.g. posted speed limit, traffic volume, functional class, and number of through lanes) used to classify facilities into four levels of traffic stress. The deterrents to bicycling are explored in the literature review to assist in the refining of the criteria and the current state of bicycle quality of service tools is explored to understand state of the practice. The four roadway and bikeway levels of traffic stress used in the LTS tool should correspond to types of bicyclists. For this reason bicyclist typology is also analyzed in the literature review.

2.1 Bicyclist Typology

Bicycle riders have historically been classified in the United States in an attempt to understand the facility characteristics that appeal to different types of bicyclists. The four types of bicyclists typology introduced by Roger Geller and modified by Misra et al attempts to classify both current and potential bicyclists [4] [6]. By understanding the needs of current and potential bicyclists, the appropriate facilities can be designed and built, which may increase the mode share of bicycling in the U.S.

While it is generally recognized that it is beneficial to segment the population based on a bicycling typology, there has been little research conducted on the topic. Segmenting such a heterogeneous group as bicyclists (not even considering potential bicyclists) creates a great challenge. As noted in a 2010 report for Department for Transport, London, “cyclists are a highly diverse, highly segmentable population” [10]. The report goes on to caution that it is, “important to remember that individuals may belong to more than one group: for example, a single person may commute to work, use cycling as an escape activity with their family, and sometime cycle with their children to the shops” [11].

2.1.1 Skill Level or ABC Bicyclists

In a 1994 report, *Selecting Roadway Design Treatments to Accommodate Bicycles*, the FHWA outlined bicycle facility designs that would appeal to all bicyclist types [12]. The report classified cyclists based on skill level as Advanced Bicyclists, Basic Bicyclists, and Children. The 1999 AASHTO report, *Guide for the Development of Bicycle Facilities,* utilized the FHWA's 1994 report's use of the ABC bicycle types [13]. The ABC typology categorized bicyclists based on their skill level with the assumption that as bicyclists became more skilled they would advance into a higher categorization for example from a "B" cyclists to an "A" cyclist [5]. While, the reports encouraged designing bicycle facilities for "B" or basic bicyclists, neither report attempted to quantify the proportion of the population that could be classified into each category.

2.1.2 Level of User Skill and Comfort

The 2012 AASHTO Guide for the Development of Bicycle Facilities categorizes bicyclists based on age, experience and confidence [3]. The guide asserts that children and older adults have more limited riding skills than younger and middle aged adults. The guide also identifies two types of bicyclists. The first is the Experienced and Confident rider type which includes, "bicyclists who are comfortable riding on most types of facilities," such as roads without any bicycle specific treatments. However, some Experienced and Confident riders prefer low-traffic residential streets or separated paths [3]. The other type identified by AASHTO is Casual and Less Confident riders. This type of bicyclist represents a wide range of people as the category includes the majority of the population. Casual and Less Confident riders may ride frequently for many purposes, bicycle occasionally and only ride on low-traffic streets or separated paths, ride for recreation possibly with children, or use the bicycle as a necessary mode for transportation [3]. This type will only choose to bicycle frequently if a well-connected network of, "visible, convenient, and well-design bicycle facilities," is available [3].

2.1.3 Bicycling Frequency

Research studies often classify bicyclists by the frequency that they ride. Winters et al classified bicyclists into the following riding frequency categories;

- regular cyclists who cycle at least once a week
- frequent cyclists who ride at least monthly
- occasional cyclists who ride at least once a year
- potential cyclists who had no ridden in the previous year, but would like to ride in the future

[14].

The research focused on the motivators and deterrents to bicycling and found that the top motivators across all riding frequency types were, "routes away from traffic, noise and pollution; routes with beautiful scenery; and paths separated from traffic" [14].

Dill and Voros also classify bicyclists by frequency to aid in analyzing the factors that affect bicycling demand. The riding frequency types used in the study are:

- Non-Cyclists who never ride a bicycle or who occasionally ride but did not ride during the past summer of in non-summer months
- Irregular Cyclists who rode in the past summer, but not in non-summer months or those who rode year-round, but less than once a week
- Regular Year-Round Cyclists who rode year-round at least once a week
- [15]

Dill and Voros suggested that the Irregular Cyclist type could be targeted for, "policy, planning, and marketing efforts," as they would be the easiest population to increase the amount of bicycling [15]. Participants were also asked if they had made a utilitarian trip by bicycle in the past summer. Men and younger adults were a higher proportion of regular and utilitarian bicyclists with a significant drop off of regular and utilitarian bicycling among participants at age 55 and over [15].

Sanders categorized bicyclists by the frequency that they ride to see if riding frequency affects bicyclists perception of traffic risk [16]. The categories are as follows;

- Non-cyclist
- Infrequent cyclist
- Frequent cyclist

The study found that bicyclists who ride frequently are more likely to fear commonly reported crash types, potential cyclists feared crash types that are reported less frequently, and occasional bicyclists report the most fear of all bicyclists [16]

Ahmed et al. categorized bicyclists by riding frequency to assist in analyzing bicyclist commuter travel behavior. Riders were categorized as Committed Cyclists who rode to work more than three days a week or Casual Cyclists who rode to work no more than three days a week. The research found that weather affected the decision to bicycle for all types, however, Casual Cyclists were most affected by adverse weather conditions [17].

2.1.4 Stated Comfort Level: Four Types of Cyclists

In 2006, Roger Geller, the City of Portland's Bicycle Coordinator, released a paper proposing a new typology for current and potential bicyclists. Unlike previous typologies, Geller's typology attempted to categorize the entire population and not just current bicyclists [4]. Users are categorized by their comfort riding on different types of bicycle facilities, including conventional bicycle lanes, shared travel lanes, shared use paths, and more. Geller classified bicyclists based on four categories: The Strong and Fearless, The Enthused and Confident, The Interested but Concerned, and No Way No How. The Strong and Fearless type represents individuals who would bicycle in almost any road or traffic condition with no consideration of separated bicycle facilities. The Enthused and Confident type is comfortable riding in the roadway with motor vehicles but they prefer their own facilities. The Interested But Concerned type are interested in bicycling, however, they are unwilling to bicycle on shared roadways with high motor vehicle travel speeds and traffic volumes and will only bicycle on roadways with low speeds and low traffic volumes like neighborhood roads and prefer to ride on bicycle or shared-use only facilities. The No Way No How type represents people who would never considering bicycling for various reasons from physical inability to bicycle, topography, or lack of interest [4].

Geller estimated the proportion of Portland's population which fell into each category and asserted that the Interested but Concerned category makes up approximately 60 percent of Portland's population, the Enthused and Confident approximately seven percent, and the Strong and Fearless less than one percent [4]. While the No Way No How category consists of the remainder of Portland's population at 33 percent [4]. The Portland Bicycle Master Plan stated that its target was the Interested but Concerned category as the category was seen as the market segment that could most easily be accommodated to encourage increased rates of bicycling and increased bicycle mode share in the City [5]. Geller's four types of bicyclists have limitations as they were created based on his professional experience as a planner and not on empirical evidence [4]. The wide adoption of the typology by professional planners speaks to the desire for a typology, which considers both current and potential bicyclists. However, caution must be taken until the typology can be verified and refined with additional research.

Geller's typology has created a great deal of discussion with bicycle planners and advocates and has been used in numerous city or regional plans [5]. Recent plans include, Los Angeles, CA (2011), Seattle, WA (2012 progress report), Palo Alto, CA (2011 draft plan), and more [5]. However, little research has been conducted to validate Geller's typology. Jennifer Dill and Nathan McNeil's 2012 report, *Four Types of Cyclists? Examining a Typology to Better Understand Bicycling Behavior and Potential,* examined Geller's typology by attempting to reproduce the four typologies and their proportion of the population in the City of Portland [5]. Dill and McNeil conducted a random phone survey using both landline and mobile phones of 908 adults in Portland, Oregon and weighted the data to better reflect the population [5]. The survey participants were placed into one of the four categories based on their responses; 4% Strong and Fearless, 9% Enthused and Confident, 56% Interested but Concerned, 31% No Way, No How. Dill and McNeil's results closely match Geller's approximation of the proportion of the population of Portland that would fall into each category. Additional surveys on the proportion of the population that falls into each category should be conducted in other cities in the U.S. to verify that the typology can be applied the same way through the U.S. or if adjustments should be made.

2.1.5 Sociodemographics and the Four Types of Cyclists

Research by Misra et al. further investigated the Geller classification of bicyclists by comfort level and offered a modified version of the typology. The Misra et al. study modified the Geller typology by dividing the Interested but Concerned group into two groups: Comfortable but Cautious and Interested but Concerned. The Comfortable but Cautious group was hypothesized to include female bicyclists and/or older bicyclists who are bicycle enthusiasts, but may be more risk adverse which makes the type appear less confident than the Enthused but Confident type (which was hypothesized to be majority male and younger). The Interested but Concerned type continued to contain people who were interested in bicycling, but who had significant safety concerns [18].

The researchers also explored the potential correlation of socio-demographic variables such as age, gender, and income with different levels of comfort [18]. The study used data collected from bicyclists who used the Cycle Atlanta app to log their bicycle trips. Participants self-classified themselves as a type in a modified version of Geller's four types of bicyclists and then the categorization was then regressed against the participant's socio-demographic variables, frequency of bicycling, and riding history or how long the user had been bicycling to identify any correlation [18]. The study then used a stated preference survey to explore the potential that the four types preferred distinct or similar infrastructure design and traffic characteristics. Survey results showed that participants across all categories of the four types preferred separated facilities and low traffic speed and volume [18].

The study showed that sociodemographic characteristics, particularly age, gender, and rider history, were significant predictors of people's self-classification into different types [18]. Using socio-demographic characteristics to predict user type can help predict facility design needs for a city as potential cyclist's preferences can be predicted [18]. Misra et al. plan future research, which will study people's infrastructure preference based on revealed preference rather than stated preference.

2.2 Variables That Influence the Choice to Bicycle

Bicycle quality of service tools classify roadways and bikeways by characteristics that affect riders bicycling experience. The review of literature on variables that deter or encourage the choice to bicycle were used in this thesis to update the traffic, roadway, and bikeway characteristics used in the LTS tool.

2.2.1 Weather

Prevalent research has identified three weather factors, which affect the decision to bicycle: temperature, precipitation, and wind [19], however, the research is mixed on the influence of these weather factors on bicycling mode share.

Parkin, Wardman, and Page and Nankervis found that people's decision to not bicycle is more heavily impacted by cold weather than hot weather [20] [21]. However, Buehler and Pucher found that cycling mode share was lower in cities with more days per year with temperatures over 90°F. Buehler and Pucher also found a, "statistically significant relationship between the number of cold days per year and bike commuting" [22].

Buehler and Pucher did not find that precipitation was a major deterrent [22], however, other research determined that heavy rain was more of a deterrent than temperature [23] [21] [24]. While Dill and Carr found precipitation to be negatively related to bicycle mode share, Nankervis argues that wind has a significant influence on the decision to bicycle. Yet, the effect of wind has not been studied extensively [19] [21].

While cycling mode share may be affected by these three weather factors the effect may be over emphasized and mode share may be more impacted by other factors. Pucher, Komanoff, and Schimek note that three of the case study cities with high bicycle mode share in their 1999 report had mild winters (Davis, San Francisco, and Seattle) and that high temperatures and humidity in the southern United States discourage cycling. However, Pucher et al. recognize that northern Europe has a much higher cycling mode share than southern Europe despite “mostly cloudy days and frequent rain and drizzle” in the north and “drier, sunnier, and warmer” days in the south [25].

2.2.2 Actual and Perceived Safety

The actual safety of bicycling is a major deterrent to deciding to bicycle, however, research has shown that increasing the mode share of bicycling increases the actual safety of bicycling [26]. In the U.S., cycling trips represent only 1% of trips, yet 2% of all traffic fatalities in 2012, which was a 6% increase in fatalities [27] from 2011. A great deal of work will need to be done to improve the actual safety of bicycling, which can be accomplished with behavioral changes by both bicyclists and motor vehicle drivers and increased bicycle infrastructure [25].

However, the impact of actual safety risks from the choice to bicycle in the U.S. is magnified by the public perception of bicycling accidents as an inescapable element of bicycling and often blaming bicyclists for placing themselves in peril [19] [25]. In contrast, motor vehicle accidents are not often attributed to driving as inherently dangerous. Pucher suggests that not only actual bicycling safety must be improved, but also the perception of bicycling as inherently dangerous, which he ascribes as, “a difficult task at best” [25].

2.2.3 City Size and Population Density

Numerous studies have shown that cities or metropolitan areas with higher levels of density have higher cycling mode share than areas with low density [22] [28][19] [29]. Pucher asserts that no city with a population of 2 million people or larger has a bicycle mode share of 10% or more and that less sprawling cities encourage the choice to bicycle as more amenities are accessible at a short distance, connectivity is increased, and less obstacles such as bridges and expressways exist [25].

2.2.4 Public attitude toward bicycling

In countries with high bicycle mode share, bicycling is a common activity for people young and old, of all socioeconomic levels, and balanced by gender. However, in the U.S., the majority recreational and commuters bicyclists are young males [25]. In the U.S. bicycling is considered abnormal, however, in countries where bicycling is considered "normal," people choose bicycling as a mode when it is convenient and motor vehicle drivers show more respect and tolerance for bicyclists. This is likely because many drivers are bicyclists on other days or have family or friends who bicycle frequently [25]. Pucher identifies this cycle of considering bicycling abnormal as self-perpetuating when there are few bicyclists. Increasing the mode share of bicyclists with improved infrastructure design may be one effective way to end the cycle and create a public perception of bicycling as "normal."

2.2.5 Relative Cost of Motor Vehicles and Public Transit

The cost of driving a motor vehicle is also higher in countries with a high bicycle mode share. In contrast, driving is relatively cheap in the U.S. due to a low gas tax, infrequent road and bridge tolls, and easily accessible free or cheap parking [25]. A robust transit system in many European countries makes not owning a car more feasible, which encourages alternative transportation modes including bicycling [25]. In contrast, a robust public transit system is only available in a small number of cities in the U.S. making ownership of a car more of a necessity. This, combined with the low cost of utilizing a motor vehicle, encourages the use of motor vehicles even for short trips that could be walked or biked [25].

2.2.6 Income and Sociodemographics

It is well established in the literature that households with higher incomes are more likely to own a car [25]. Previous studies have found that households with more cars are less likely to bicycle and that students are more likely to bicycle as they are less likely to own a car [30] [31] [19].

Previous research has suggested that women bicycle less than men because of lack of bicycle facilities. However, research by Smart et al. found that women disproportionately drive children around and make house-hold serving trips. These types of trips do not lend themselves well to bicycling. In households where both partners work fulltime and have children, women make 1.6 times as many child-serving trips and 1.5 times as many grocery trips as their male partner [32]. This difference exists for both high and low earning women. The researchers assert that, "disproportionate house-hold travel burdens borne by women," is culturally based and will not change unless, "gender socialized norms begin to change more quickly" [32].

2.2.7 Topography

While there is consensus that hilliness affects route choice and the choice to bicycle [15] [22][33] [34] [35] there is no standard objective measure of hilliness [33] [22]. The impact of hilliness on the decision to bicycle as compared to other variables is thought to be moderate [19]. Hilliness may be a more important factor for route choice and the decision to bicycle for certain groups such as commuters, women, inexperience cyclists, or children [36] [19].

2.2.8 Bicycle Parking and End of Destination Infrastructure

While there is no consensus on the impact of end of destination amenities such as showers on the decision to bicycle, there is clear research on the impact of the availability of parking spaces at the end of destination on the decision to bicycle [19]. Research has shown that the availability of bicycle parking improves the cyclists' perception and when located at transit stops encourages multi-modal trips [19].

2.2.9 Distance from Origin to Destination

Godfrey and Morency's research to estimate bicycling latent demand on the island of Montreal, Canada attempted to estimate the amount of car trips from the 2008 O-D survey of the greater Montreal area that could be converted to bicycling trips. Among a number of criteria in choosing if a trip could be converted from car to bicycle, was a threshold distance. The researchers set the threshold based on observed behaviors of cyclists revealed in the 2008 O-D survey. They determined that the threshold distance varied widely among bicyclists, but was most obviously broken down by gender and age, as in Figure 1 below [19]. However, there are limitations to setting distance thresholds in this manner as the distance threshold is only being set by current bicyclists with no consideration of potential bicyclists. Other research has shown that potential bicyclists may have a shorter distance threshold than current bicyclists [33]. Trip chaining can also deter the decision to bicycle, especially trips made for shopping purposes due to the need to carry heavy loads and trips which require transporting other people [33] [19]. Trip chaining also increases the chance that the total distance exceeds the distance threshold for an individual [19].

	Sample (observed trips)		Distance Threshold [km (mi)]	
Age Group (years)	Men	Women	Men	Women
5–12	86	48	1.99 (1.24)	1.27 (0.79)
13–17	79	25	3.56 (2.21)	2.95 (1.83)
18–44	971	671	5.47 (3.39)	4.38 (2.72)
45–59	490	261	5.44 (3.38)	5.19 (3.22)
60 and older	193	59	4.00 (2.48)	2.00 (1.24)

Figure 1: Bicycling Distance Thresholds [19]

2.2.10 Traffic, Roadway, and Bikeway Characteristics

Research has shown that “cycle-friendly” infrastructure has a positive impact on the rate of bicycling [37] [22] and some research has shown which facility designs potential and current bicyclists favor. Currently there is limited research on the impact of innovative bicycle facility designs such as protected cycle tracks. However, Winters’ studies of 2,149 current and potential cyclists across Metro Vancouver found that subjects expressed a clear preference for separated facilities, especially women, people with children, and “occasional and potential cyclists” [14] and Misra et al.’s research showed that all cyclist types preferred separated bicycle facilities [6]. Other research has found that women prefer separated bicycle facilities [38]. Winters analysis of potential motivators and deterrents to bicycling found that environmental and engineering factors carried the strongest influence; including facility design, safety issues, topography, scenery, and weather [14].

After a review of the literature it was determined that the refinement of the LTS tool would focus on traffic, roadway, and bikeway characteristics, which were the basis of the MTI LTS tool. Additional variables such as topography and distance from origin to destination are important variables to consider in future research which analyzed route choice.

2.3 Models to Estimate Bicyclist Perception of the Quality of Service of a Facility

While design guidance is available, especially from NACTO and AASHTO, for the installation of bicycle facilities, little guidance is available to assist with the selection of the appropriate bicycle facility for the specific location [39]. Quality of service tools allow for alternative analysis of various facility designs for a specific location. Quality of service tools for motor vehicles such as LOS (level of service) or other evaluation tools provided in the *Highway Capacity Manual 2010* (HCM) are extensively peer reviewed and based on research and application occurring over multiple decades. However, bicycle quality of service tools are comparatively less developed and will require extensive research to be fully developed [40] [39].

This section will consider the following bicycle quality of service tools; Highway Capacity Manual (HCM) 2010 Bicycle Level of Service (BLOS), Bicycle Compatibility Index (BCI), Bicycle Environmental Quality Index (BEQI), Bike Score, Bicycle Quality Index (BQI), and Level of Traffic Stress (LTS). The criteria required, strengths, and weakness of each quality of service measure is discussed below.

2.3.1 Highway Capacity Manual (HCM) 2010 BLOS

The multimodal LOS tools included in the HCM are the industry standard for engineers. The 2010 HCM, for the first time, incorporated motor vehicle, transit, pedestrian, and bicycle LOS into the same chapters instead of including pedestrian and bicycle LOS in their own chapter. However, the LOS measures are not meant to be combined for a blended multimodal LOS for a facility. Each mode has their own perspective and design needs and blending the LOS has the potential to ignore the particular needs of one mode [7]. The HCM recognizes that urban streets are used by multiple travel modes and facility designs intended to improve the service level of one mode may have a negative impact on the service level of another mode. The HCM attempts to accommodate the design needs to all travel modes by including LOS for all modes. However, it is unknown how frequently the LOS for all travel modes is analyzed when LOS is utilized in practice.

This report is focused on the HCM BLOS, which can be used to analyze link, segment, intersection, or facility LOS. A link is the section of street between two intersections, while the segment is the link plus the nearest downstream controlled intersection [7].
BLOS is a tool designed to measure quality of service by stratifying multiple performance measures to determine levels of service ranging from LOS F as the worst condition and LOS A as the best operating condition [7]. The A - F levels of service attempt to simplify complex calculations of the interaction of various performance measures, so that the LOS tool can be useful for decision makers and the public [7]. BLOS is calculated with the use of a linear function with weights assigned to independent variables and produces a numerical score

ranging from 0 to 6 with the numerical score relating to the LOS A - F grade as follows: A ≤ 2.00, 2.00 < B≤ 2.75, 2.75 < C ≤ 3.50, 3.50 < D ≤ 4.25, 4.25 < E ≤ 5.00, and F > 5.00 [39]. The HCM BLOS model was developed by showing videos of various bicycle facilities to participants who were asked to rank how satisfied they were with the bicycle facilities on a six-point scale ranging from "very dissatisfied" to "very satisfied" [39].

The most notable difference between the bicycle and motorized vehicle service criteria is that LOS is concerned with the mobility provided by the street, which is characterized by through-vehicle travel speed, while BLOS considers both performance measures like speed and "basic descriptors of the urban street character" such as number of driveways, access points, motor vehicle volumes and speeds, on street parking, pavement condition, etc. [2]. BLOS is likely more problematic as a quality of service measure as compared to motor vehicle LOS due to the increased number of criteria which the HCM considers.

2.3.1.1 Criteria (for link HCM BLOS)

- Width of outside lane
- Width of bike lane
- Width of shoulder
- Proportion of occupied on-street parking
- Vehicle traffic volume
- Vehicle speeds
- Percentage of heavy vehicles
- Pavement condition
- Presence of curb
- Number of through lanes

[7]

The following linear equation is used in the model:

$$\underbrace{I_{b,link}}_{\text{Bike Link LOS Score}} = \underbrace{0.760}_{\text{Constant}} + \underbrace{F_v}_{\text{Volume Factor}} + \underbrace{F_S}_{\text{Speed Factor}} + \underbrace{F_p}_{\text{Pavement Condition Factor}} + \underbrace{F_w}_{\text{Cross-Section Factor}}$$

$$F_p = \frac{7.066}{\underbrace{P_c}_{\text{Pavement condition rating (1–5)}}^2}$$

$$F_v = 0.507 \ln\left(\frac{\overbrace{v_{ma}}^{\text{Adjusted midblock vehicle flow rate (veh/h)}}}{4\underbrace{N_{th}}_{\text{Number of through lanes in travel direction}}}\right)$$

$$F_S = 0.199\left[1.1199 \ln(\underbrace{S_{Ra}}_{\text{Vehicle running speed (>= 21 mi/h)}} - 20) + 0.8103\right](1 + 0.1038\ \underbrace{P_{HVa}}_{\text{Adjusted percent heavy vehicles}})^2$$

Figure 2: HCM 2010 BLOS Equation [41]

2.3.1.2 Strengths

HCM BLOS has many strengths including its basis in bicyclists' perception of facility characteristics, its focus on facility design that is directly under the influence of operating agencies, and that it is directly measurable in the field. HCM LOS A-F for motor vehicles is widely used in transportation which promotes familiarity of the HCM BLOS A – F. HCM BLOS considers pavement condition as one of the facility criteria of the model. Current and potential bicyclists in Metro Vancouver ranked routes with, "potholes or uneven paving," as a significant deterrent to riding [14]. However, current and potential bicyclists surveyed in Portland, Oregon ranked "poorly maintained streets or rough surfaces" low as an environmental barrier keeping them from biking more [15].

2.3.1.3 Weaknesses

HCM BLOS has the following primary weaknesses: lack of transparency for the public and decision makers, a focus on arterial roadways over local roadways, lack of sensitivity to driveway type, lack of consideration of innovative bicycle facilities, intersection LOS that requires further refinement, acceptance of wide outside motor vehicle lanes, and limited validation with surveys. While HCM BLOS A – F is familiar to transportation professionals, it is not well understood by the public and decision makers, which limits the quality of service measure's ability to assist in the selection of the appropriate bicycle facility for the specific location. HCM BLOS focuses on assessing arterials and collectors and does not consider local roads, which research has shown are preferred by cyclists. Winter's survey of Metro Vancouver residents found that residential streets were the most commonly used route type and that the majority of routes that were analyzed detoured from the shortest distance route to use local roads even if the distance was up to 10% longer [10]. By focusing only on BLOS for arterials and collectors, there is a potential to bias the allocation of new bicycle facilities to arterials and collectors with a lack of consideration for how local streets fit into the network.

HCM BLOS treats access points and driveways the same without considering if they are residential or commercial. This is important because commercial driveways and access points are more likely to have higher volumes of motor vehicle traffic, a potential negative quality of these facilities. The video survey that the HCM 2010 BLOS is based on only asked for participants' satisfaction with bicycle lanes or roadways with no bicycle facilities [8]. Innovative bicycle facilities such as protected cycle tracks were not considered. Future versions of the HCM BLOS will likely include these innovative bicycle facilities, however, the current version lacks sensitivity to these facility types. The video footage was shown to 120 participants in only four cities, urban and suburban. Additional video surveys should be conducted since the sample size is limited [8].

Parks et al. assert that one of the limitations of HCM BLOS is its linear regression formulation which makes the model less sensitive to the variables that it includes. The model is less sensitive due to its large constant in the regression model (C=2.85) which makes it difficult to achieve an LOS A or B and causing HCM BLOS scores to cluster thus thwarting the goal of the HCM BLOS to, "distinguish between design alternatives for the purpose of evaluation" [39]. The link LOS does enable the full range of potential LOS scores (A – F) due to its smaller constant, however, link LOS does not include any intersection characteristics which reduces the value of the model [39]. While HCM BLOS can be used to calculate link, segment, intersection, and facility LOS, the HCM states that segment and intersection BLOS have limitations and recommend that link LOS be used [2] [39]. BLOS also cannot model the service level for segments bounded by all-way STOP-controlled intersections of roundabouts and segments with grades more than two percent [2].

BLOS allows for wider outside motor vehicle travel lanes, with the assumption that bicyclists will feel more comfortable traveling in the lane if vehicles have more room to pass them. However, research has shown that bicyclists prefer separate paths and bicycle lanes over riding in mixed traffic with motor vehicles [15] [35] [42] [43] [14] [33]. Research on the position of bicyclists and motorists in bicycle lanes with on street parking compared to wide outside shared travel lanes with on street parking found that bicyclists were more likely to travel in the parked vehicle 'dooring' zone even though they had larger total lane width. This may be due to the markings of bicycle lanes clearly showing bicyclists and motorists where to position themselves on the roadway, as compared to a shared travel lane [44].

Many of these issues may be resolved by proposed revisions to Chapters 16, and 17 of the 2010 HCM being developed by Ridgway et al. who are sponsored by the TRB Bicycle Transportation Committee [8]. These researchers are focusing on studying users' ratings of standard and innovative bicycle facilities, while accounting for user experience and demographics. Research will be conducted in a variety of cities and suburbs so that a wide range of facilities and geographic areas are represented [8]. However, the HCM is infrequently updated with previous editions being released in 2010, 2000, 1985, 1965, and the first edition in 1950 [45].

2.3.2 Bicycle Compatibility Index (BCI)

The BCI was developed as a methodology to determine the perceived comfort level of cyclists within certain traffic operating conditions and geometric conditions of the roadway [46]. Development of the model was funded by the FHWA. The BCI was developed before BLOS was included in the HCM. Bicyclists' perception of comfort was rated like the HCM LOS A - F with A representing the most comfortable and F the least comfortable.

2.3.2.1 Criteria

A regression model was developed to predict the overall perceived comfort level of cyclists and included the following significant variables:

- Number of lanes
- Directions of travel
- Curve lane
- Bicycle lane
- Paved shoulder
- Parking lane width
- Gutter pan width
- Traffic volume
- Speed limit
- 85th percentile speed
- Driveway density
- Presence and type of sidewalks
- Presence and type of medians
- Type of roadside development

[46]

Adjustment factors were also developed for the presence of large trucks or buses, vehicles turning right into driveway, and vehicles pulling into or out of on-street parking spaces. The regression model and variables are shown in Figure 3 below.

$$\text{BCI} = 3.67 - 0.966\textbf{BL} - 0.410\textbf{BLW} - 0.498\textbf{CLW} + 0.002\textbf{CLV} + 0.0004\textbf{OLV} + 0.022\textbf{SPD} + 0.506\textbf{PKG} - 0.264\textbf{AREA} + \textbf{AF}$$

where:

BL = presence of a bicycle lane or paved shoulder ≥ 0.9 m
no = 0
yes = 1

BLW = bicycle lane (or paved shoulder) width
meters (to the nearest tenth)

CLW = curb lane width
meters (to the nearest tenth)

CLV = curb lane volume
vehicles per hour in one direction

OLV = other lane(s) volume - same direction
vehicles per hour

SPD = 85th percentile speed of traffic
km/h

PKG = presence of a parking lane with more than
30 percent occupancy
no = 0
yes = 1

AREA = type of roadside development
residential = 1
other type = 0

AF = $f_t + f_p + f_{rt}$

where:

f_t = adjustment factor for truck volumes
(*see below*)

f_p = adjustment factor for parking turnover
(*see below*)

f_{rt} = adjustment factor for right turn volumes
(*see below*)

Adjustment Factors

Hourly Curb Lane Large Truck Volume[1]	f_t
≥ 120	0.5
60 - 119	0.4
30-59	0.3
20-29	0.2
10-19	0.1
< 10	0.0

Parking Time Limit (min)	f_p
≤ 15	0.6
16 - 30	0.5
31 - 60	0.4
61 - 120	0.3
121 - 240	0.2
241- 480	0.1
> 480	0.0

Hourly Right Turn Volume[2]	f_{rt}
≥ 270	0.1
< 270	0.0

[1] Large trucks are defined as all vehicles with 6 or more tires.
[2] Includes total number of right turns into driveways or minor intersections along a roadway segment.

Figure 3: BCI Equation and Adjustment Factors [46]

2.3.2.2 Strengths

The BCI LOS tool has the following primary strengths: public education on facility condition, prioritization of facility improvements, assessment of LOS of future roadways, and a robust range of sites included in the survey to develop the tool. The BCI tool can be used for operations analysis to determine BCI LOS for all segments. This information can be used to educate the public on which LOS level they should expect for a segment. BCI LOS allows for the prioritization of segments that are categorized as a low LOS for targeted facility improvements which increase the segments' LOS. The model is also useful for design of new roadways to determine if they would be perceived as comfortable for bicyclists based on the BCI LOS. BCI can also be used for long-range planning in determining if a roadway segment will be comfortable for bicyclists based on forecasted vehicle traffic volume and planned roadway re-designs [46].

The BCI tool was developed with video surveys of 202 participants ranging from 19 to 74 years of age and a range of experience levels. Males were slightly overrepresented as 60% of the participant pool. The participants rated the comfort level of 67 sites using a six-point comfort level rating scale. The sites had vehicle speeds ranging from 40 to 89 km/h or approximately 25 to 55 mph, and 2,000 to 6,000 vehicles per day, which represents a robust range of sites [46].

2.3.2.3 Weaknesses

The two primary weaknesses of the BCI LOS are: reliance on skill level typology and inability to analyze segments with varying geometric and operation characteristics. Participants for the survey used to develop the tool were chosen to represent a variety of experience levels. The assumption as with the previously discussed bicyclist typology, Skill Level or ABC Bicyclists, is that as a person becomes a more experienced cyclist, they will become more comfortable with lower rated roadways. However, research on perceived comfort such as LTS suggests that people may not become more comfortable with stressful roadways even if they become more experienced bicyclists. Also, the BCI can only evaluate roadways segments, "where a segment is defined as a section or roadway between intersections where the geometric and operational characteristics remain constant" [46]. This means that the model cannot evaluate intersections or roadways with varying geometric and operational characteristics.

2.3.3 Bicycle Environmental Quality Index (BEQI)

The BEQI model was developed by the San Francisco Department of Public Health's Environmental Section through a survey of transportation professionals and members of the bicycling community. Survey participants were asked to weight the most important variables that affected their perception of bicycle facility quality. Based on the responses the variables, "were combined in an index that ranged from 0 to 100" [39]

The index ranks facilities as follows:

- 100 to 81: highest quality, many important bicycle conditions present;
- 80 to 61: high quality, some important bicycle conditions present;
- 60 to 41: average quality, bicycle conditions present but room for improvement;
- 40 to 21: low quality, minimal bicycle conditions; and
- 20 to 0: poor quality, bicycle conditions absent

[39]

2.3.3.1 Criteria

The BEQI tool includes 22 variables:

- Bicycle lane markings
- Bicycle lane slope
- Bicycle parking
- Bicycle/pedestrian scale lighting
- Connectivity of bicycle lanes
- Dashed intersection bicycle lane
- Driveway cuts
- Left turn bicycle lane
- Line of sight
- No turn on red sign(s)
- Number of vehicle lanes
- Parallel parking adjacent to bike lane/route
- Pavement type/condition
- Percentage of heavy vehicles
- Presence of a marked area for bicycle traffic
- Presence of bicycle lane sign
- Presence of trees
- Retail use

- Traffic calming features
- Traffic volume: average number of vehicle per day
- Vehicle speed
- Width of bicycle lane

[47]

The factors with the highest weight in the BEQI tool are bicycle facility type, bicycle facility width, pavement type, pavement condition, slope, pavement markings, connectivity, driveway cuts, and presence of trees [39].

2.3.3.2 Strengths

The primary strength of the BEQI tool is the software that is publicly available to execute the tool. Other strengths include intuitive interpretation of the rating scale of facilities and that BEQI facility ratings matched survey participants perceptions of facilities. The BEQI tool has a Microsoft Access database application that makes input and evaluation of data relatively easy and the City of San Francisco has published two reports on the software and data inputs [39]. The quality of bicycle facilities are rated on a 0 to 100 scale, which may be a more familiar format for the public who may not intuitively understand the LOS A – F scale as easily [39]. Parks et al. compared the score that the BEQI model gave various facilities and the perception of survey participants. The BEQI model more closely matched the survey results than the HCM BLOS [39].

2.3.3.3 Weaknesses

The weaknesses of the BEQI tool include the tool being difficult to implement outside of San Francisco, requiring a high number of variables, requiring data that needs to be gathered manually, being developed with the input of transportation professionals and current bicyclists with no input from potential bicyclists. However, the Microsoft Access database application is more difficult to implement outside of the City of San Francisco, which may be a result of the model being developed specifically for that location. BEQI requires 22 variables for the model which is larger than the other models discussed in this report. Many of the 22 variables can be gathered remotely, however, some of the variables require extensive site visits such as determining signage, lighting, landscaping, etc. [39] [47]. The model was developed by surveying transportation professionals and members of the bicycling community. People who do not currently bicycle, but who may be willing to with more comfortable bicycle and roadway facilities were not included in the survey. This may make it less sensitive to the variables that current non-users find more comfortable [48].

2.3.4 Bike Score

The Bike Score tool was developed by the company Walk Score. Facilities are ranked from 0 to 100 to indicate if they are “good for biking” [49]. Bike Score’s rankings are as follows:

- 90 to 100 Biker’s Paradise: Daily errands can be accomplished on a bike
- 70 to 89 Very Bikeable: Biking is convenient for most trips
- 50 to 69 Bikeable: Some bike infrastructure
- 0 to 49 Somewhat Bikeable: Minimal bike infrastructure

[49]

Bike Score ranks a location based equally on bicycle facilities, hills, destinations and road connectivity, and bicycle commuting mode share in the surrounding area [49]

2.3.4.1 Criteria

The following criteria are used in the Bike Score index:

- Bike lanes
- Hills
- Destinations and road connectivity
- Bike commuting and mode share

[49]

2.3.4.2 Strengths

Bike Score has two primary strengths, the public's familiarity with the company and its other tools and a well-designed website that calculates the Bike Score and displays the results in an easily readable map. Walk Score was created by the same company who developed Bike Score. Walk Score is a popular tool for assessing the walkability of an area. Due to the public's familiarity with Walk Score it is likely that Bike Score would be an intuitive tool. Bike Score also has a user friend web interface with easily understood maps.

2.3.4.3 Weaknesses

The primary weakness of the Bike Score tool is the lack of transparency provided. The public can only access Bike Score data through the Walk Score company. This limits the tools usability for planning, design, and research purposes. It is unknown how much the Bike Score data would cost to purchase. Along with potentially prohibitive costs there are also concerns about lack of transparency with the data quality and methods used to calculate Bike Score. For instance, bicycle facility data is provided by city governments [49]. It is not known how accurate this data is and how often it is updated. City governments also tend to classify bicycle facilities using different methodologies.

2.3.5 Mineta Transportation Institute (MTI) Level of Traffic Stress (LTS)

The Mineta Transportation Institute study on level of traffic stress focused on creating methods to measure low-stress connectivity. The researchers classified roadways and bikeways into four levels of traffic stress according to a modified version of Geller's four types. LTS 1 included facilities suitable for children; LTS 2 facilities characteristics were based on the Dutch CROW Design Guide and were intended to be comfortable for most adults; LTS 3 and LTS 4 present tolerance for characteristics of higher stress [1]. Table 1 provides a more detailed description of the four types of MTI LTS.

Table 1: MTI LTS Descriptions [1]

LTS 1	Presenting little traffic stress and demanding little attention from cyclists, and attractive enough for a relaxing bike ride. Suitable for almost all cyclists, including children trained to safely cross intersections. On links, cyclists are either physically separated from traffic, or are in an exclusive bicycling zone next to a slow traffic stream with no more than one lane per direction, or are on a shared road where they interact with only occasional motor vehicles (as opposed to a stream of traffic) with a low speed differential. Where cyclists ride alongside a parking lane, they have ample operating space outside the zone into which car doors are opened. Intersections are easy to approach and cross.
LTS 2	Presenting little traffic stress and therefore suitable to most adult cyclists but demanding more attention than might be expected from children. On links, cyclists are either physically separated from traffic, or are in an exclusive bicycling zone next to a well-confined traffic stream with adequate clearance from a parking lane, or are on a shared road where they interact with only occasional motor vehicles (as opposed to a stream of traffic) with a low speed differential. Where a bike lane lies between a through lane and a right-turn lane, it is configured to give cyclists unambiguous priority where cars cross the bike lane and to keep car speed in the right-turn lane comparable to bicycling speeds. Crossings are not difficult for most adults.
LTS 3	More traffic stress than LTS 2, yet markedly less than the stress of integrating with multilane traffic, and therefore welcome to many people currently riding bikes in American cities. Offering cyclists either an exclusive riding zone (lane) next to moderate-speed traffic or shared lanes on streets that are not multilane and have moderately low speed. Crossings may be longer or across higher-speed roads than allowed by LTS 2, but are still considered acceptably safe to most adult pedestrians.
LTS 4	A level of stress beyond LTS3.

LTS criteria were developed for segments or links for the following facility types: physically separated bikeways, bike lanes, and shared travel lanes. The researchers also developed LTS criteria for right-turn only motor vehicle lanes and unsignalized intersections. The LTS criteria were applied to a case study of San Jose, CA. The researchers identified barriers to low stress bicycling especially high stress roadways at unsignalized intersections and limited access roadways. Two measures of connectivity were also introduced and executed for the study area. The first was “percent of trips connected” or the percent of trips in the regional trip table which could be completed without exceeding the specified LTS and did not exceed the acceptable level of detour. The second was “percent network that are connected to each other” and consisted of disaggregating the regional trip table from TAZ level to block level by allocating origins in the home-to-work trip table by proportion of population and destinations by land-use data.

2.3.5.1 Criteria

- Number of through lanes
- Bicycle facilities
- Posted Speed
- Width of bike lane
- Width of parking lane
- Bike lane blockage
- Right turn lane geometric information
- On street parking (by bicycle facilities)
- Signalized intersections
- Medians

[1]

Table 2: MTI LTS Criteria for Bike Lanes Adjacent to a Parking Lane [1]

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (through lanes per direction)	1	(no effect)	2 or more	(no effect)
Sum of bike lane and parking lane width (includes marked buffer and paved gutter)	15 ft. or more	14 or 14.5 ft.[a]	13.5 ft. or less	(no effect)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage (typically applies in commercial areas)	rare	(no effect)	frequent	(no effect)

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.
[a] *If speed limit < 25 mph or Class = residential, then any width is acceptable for LTS 2.*

2.3.5.2 Strengths

The main strengths of the MTI LTS include requiring more easily accessible data, being more intuitively understandable to the public and decision makers, and considering both current and potential bicyclists. The MTI LTS requires the most readily available data out of the quality of service models discussed here. Requiring easily accessible data makes the analysis of roadways and bikeways much easier for jurisdictions. MTI LTS creates results which can be understood more intuitively by the public and decision makers and has already been deployed in numerous bicycle and pedestrian plans. Unlike other quality of service tools, the MTI LTS categorizes facilities based on the preferences of the entire adult population who currently bike and who would consider biking, not just current bicyclists.

2.3.5.3 Weaknesses

The MTI LTS has four primary weaknesses: data that requires manual collection, lack of surveys to validate characteristics that affect perceived stress, lack of left-turning bicycle LTS, and lack of software to execute the tool. Even though the Mineta Institute LTS requires the most readily available data, some of the data must still be gathered manually in the field such as bike lane blockage and bicycle lane and parking lane width or remotely via Google Earth such as on street parking along bicycle lanes. The researchers approximated bike lane blockage by assuming that bike lane blockage was frequent in commercial areas and rare in all other areas [1], however, it is unknown how effective this method is for approximating bicycle lane blockage by motor vehicles. Gathering bicycle lane and parking lane width would require manual measurement in the field since Google Earth’s measurement tool isn’t accurate enough. Manual data collection can be very time consuming and may not be feasible for a larger study area.

The criteria used to classify roadways and bikeways by LTS level was not developed from surveys on the perceived stress or comfort of roadway, bikeway, and traffic characteristics for U.S. current and potential bicyclists. Some of the criteria are based off of research on U.S. bicyclist preferences, however, the majority of the criteria is based on Dutch bicycle design criteria. Further refinement of this model will require criteria to be validated with stated and revealed preference surveys of current and potential bicyclists classified by LTS level.

Many of the quality of service models discussed in this report are weak in their analysis of intersections. The MTI LTS does analyze bicycle through movements at unsignalized intersections, however, left turns by bicyclists at signalized and unsignalized intersections is not analyzed. The LTS classification of bicycle through movements at unsignalized intersections is applied to the previous link. However, this limits the applicability of the tool for route analysis since the intersection LTS should only apply to through movement restrictions and not restrictions to the previous link. If future LTS tools add the left turn LTS analysis a left turn restriction would need to be incorporated.

The MTI LTS requires ArcGIS and programming knowledge to execute since there is no software associated with the tool. This research paper was unable to execute the LTS analysis of bicycle through movement at unsignalized intersections since the analysis can only be run with a program which has not been made publicly available by MTI.

CHAPTER 3 METHODLOGY

This chapter outlines the criteria to classify roadways and separated bicycle facilities by level of traffic stress based on geometric design and traffic characteristics. These characteristics include posted motor vehicle speed limit, number of lanes on the roadway, conventional bicycle lane operating width, and the presence of or lack of on street motor vehicle parking. The goal is to create a quality of service measure which connects user tolerance for perceived traffic stress with roadway and bikeway characteristics that can be measured in the field.

Criteria were developed for links, intersections, and segments of roadway and separated bicycle facilities between intersections. Intersections are signalized and unsignalized. A link criteria matrix was developed for separated and protected bicycle facilities, bike lanes not alongside on street parking, bike lanes alongside on street parking, shared travel lanes without on street parking, and shared travel lanes with on street parking. The link and unsignalized criteria matrices were heavily informed by the MTI LTS [1]. A signalized intersection criteria matrix was developed for the through movement of bicycles on bike lanes and protected bicycle facilities with right-turning only motor vehicle lanes. They included through bike lanes in turning zones, mixing zones or combined bike lane and motor vehicle lane, and the absence of bicycle infrastructure. Signalized separated turning movements for bicycles and motor vehicles and vehicle entry markings were discussed, but not included in the criteria due to lack of research. A criteria matrix was also developed for signalized intersections with left-turning bicycles and considered bike boxes and two-stage turn queue boxes.

The criteria were chosen to attempt to account for the many factors that affect a user's perceived level of traffic stress. These criteria were drawn from research, however, additional research should be conducted on the subject to create a more robust foundation for the use of the chosen criteria and so that additional criteria can be included in the future. The MTI LTS criteria for LTS 2 were developed based on the Dutch CROW Design Manual, as the Netherlands have significantly built out separated and protected bicycle facilities and also have seen very high bicycle mode share [1]. Yet, it is unknown if the design criteria found comfortable by Dutch bicyclists would be found comfortable for American bicyclists. For this reason, it is important that additional research is conducted in cities in the U.S. Chosen criteria were limited by the availability of data. Several data sources were used and are discussed in more detail later in the chapter.

3.1 Cycle Atlanta LTS Typology

The LTS typology which is used by the Cycle Atlanta app and research project was discussed in the literature review. The Cycle Atlanta typology is a modified version of the Geller typology, in which the No Way No How type was dropped since people who would never consider bicycling would also not participate in research using an app to track people's bicycle routes. In addition, the Interested but Concerned type used in the Geller typology was split into two types with Comfortable but Cautious category intended to include female bicyclists and/or older bicyclists who are bicycle enthusiasts, but may be more risk adverse [18]. People who identify as LTS 2 Comfortable but Cautious are unwilling to bike on shared roadways with high motor vehicle speeds and traffic volume, will only bike on roadways with low speeds and low traffic volumes like local or neighborhood roads, and prefer to bike on bicycle or shared-use paths. See Table 3 for descriptions of all four Cycle Atlanta LTS types.

The Cycle Atlanta LTS typology is used in this research as the basis for the LTS roadway and bikeway criteria which are discussed in more detail later. By associating a specific typology with LTS levels for roadway and bikeway criteria it will be possible for future research to validate the criteria based on revealed and stated preference. Misra is currently conducting research to compare the LTS classification of routes that people chose to bicycle and the Cycle Atlanta LTS typology that they identify as. This research can help refine the LTS criteria for classifying roadways and bikeways.

Table 3: Cycle Atlanta LTS Typology (K. Watkins, personal communication, February 16, 2015).

LTS Typology		
LTS 1	Interested, but concerned	I have heard a lot about cycling and I am curious to try it, but I require facilities geared to cyclists before I would do so
LTS 2	Comfortable but cautious	I am comfortable on most roads, but strongly prefer facilities geared to cyclists and will chose another mode depending on facilities
LTS 3	Enthused and confident	I am confident sharing the road with vehicles but prefer facilities geared to cyclists
LTS 4	Strong and fearless	I am willing to bike in any situation and being a cyclist is part of my identity

3.2 Bicycle Network

In the context of this research, the bicycle network includes any facility that a bicycle is allowed to travel on from streets to shared use paths or greenways. In the U.S., bicyclists are allowed to travel on bicycle exclusive facilities and shared facilities, which includes any roadway that is not restricted. Bicycle facility design has diversified to include more than shared travel lanes with painted sharrows, conventional bicycle lanes, and shared use paths to innovative facility designs common in Europe such as protected cycle tracks and bike boxes. Riders have shown a preference for facilities that protect cyclists from vehicle traffic [29] [18]

Table 4 and Table 5 provide definitions for the bicycle facilities that will be discussed in this paper. The AASHTO and NACTO guidebooks are the industry standard on bicycle infrastructure design and were the sources for the definitions [3] [50]. Unlike the AASHTO guide, the NACTO Urban Bikeway Design Guide discusses the design of cycle tracks, bike boxes, bicycle signals, two-stage turn queue boxes, combined bike-lane turn lane, and enhanced shared lane markings. However, both the AASHTO and NACTO guides discuss green painted bicycle lanes, left-side bicycle lanes, contra-flow bicycle lanes, buffered bike lanes, and bike boulevards [3] [50].

Table 4: Bicycle Segment Facility Types

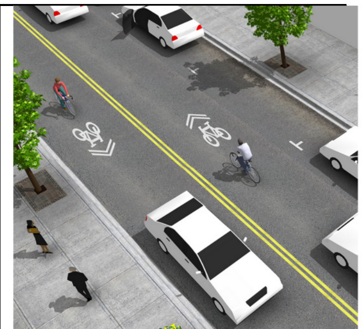
Shared Travel Lane	Shared travel lanes are roadways where bicycles may be operated (all roadways except where prohibited by statute or regulation) and where bicyclists and motor vehicles share the same travel lanes [3].	 [51]
Conventional Bike Lane	A conventional bike lane is a portion of the roadway that has been designated by striping, signage, and pavement markings for the preferential or exclusive use of bicyclists and is located adjacent to motor vehicle travel lanes and flows in the same direction as motor vehicle traffic [52].	 [51]
Shared Use Path	A shared use path is a linear corridor located in a greenway, or along a waterway, freeway, active or abandoned rail line, utility rights-of-way, and/or unused rights-of-way. Such a facility may be a short connection or a longer connection between cities [3].	 [53]
Side Path	A side path is a separated path for non-motorized users, which runs adjacent to roadways with little or no separation [3].	 [53]

Table 4: Bicycle Segment Facility Types (continued)

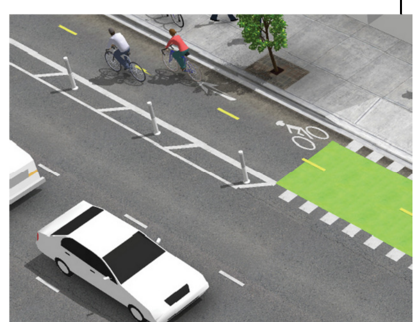
Buffered Bike Lane	A buffered bike lane is a conventional bicycle lane paired with a designated buffer space separating the bicycle lane from the adjacent motor vehicle travel lane and/or parking lane [52].	 [51]
Contra-Flow Bike Lane	A contra-flow bike lane is a bicycle lane designed to allow bicyclists to ride in the opposite direction of motor vehicle traffic. They convert a one-way traffic street into a two-way street: one direction for motor vehicles and bikes, and the other for bikes only. Contra-flow lanes are separated with yellow center lane striping [52].	 [51]
Protected Cycle Track (one and two-way)	A one-way protected cycle track is a conventional bike lane separated from traffic by raised medians or other barriers to provide physical protection from passing traffic. Two-way cycle tracks are physically separated cycle tracks that allow bicycle movement in both directions on one side of the road [52].	 [51]

Table 5: Bicycle Intersection Facility Types

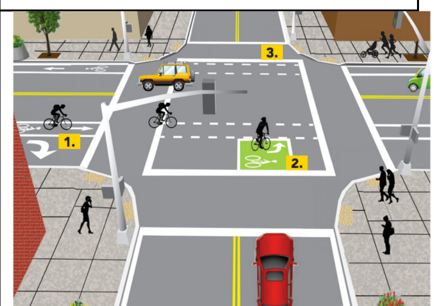
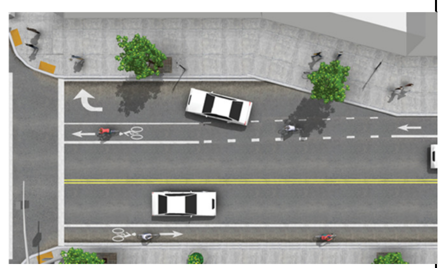
Intersection Crossing Markings	Bicycle pavement markings through intersections indicate the intended path of bicyclists through an intersection or across a driveway or ramp. They guide bicyclists on a safe and direct path through the intersection, and provide a clear boundary between the paths of through bicyclists and either through or crossing motor vehicles in the adjacent lane [52].	 [51]
Two-Stage Turn Queue Boxes	Offer bicyclists a safe way to make left turns at multi-lane signalized intersections from a right side cycle track or bike lane, or right turns from a left side cycle track or bike lane [52].	 [54]
Bike Box	A designated area at the head of a traffic lane at a signalized intersection that provides bicyclists with a safe and visible way to get ahead of queuing traffic during the red signal phase [52].	 [51]

Table 5: Bicycle Intersection Facility Types (continued)

Combined Bike Lane/Turn Lane	*A suggested bike lane placed within the inside portion of a dedicated motor vehicle turn lane. A dashed line can either delineate the space for bicyclists and motorists within the shared lane or indicate the intended path for through bicyclists. The treatment includes signage advising motorists and bicyclists of proper positioning within the lane* [52].	 [51]
Through Bike Lanes	Enables bicyclists to correctly position themselves in a through bike lane to the left of right turn lanes or the right of left turn lanes and includes a dashed bike transition lane to allow turning cars to merge across the bike lane into the turn lane and through bike lane at the intersection [52].	 [51]

3.3 LTS Quality of Service Measure

The LTS quality of service measure outlined below builds upon the MTI LTS and classifies roadways and bikeways by one of four levels of traffic stress based on traffic and geometric characteristics such as traffic volume, posted speed limit, number through lanes per direction, presence of on street parking, and bicycle facility type. Roadways and bikeways categorized at LTS 1 are the least stressful and have low traffic volumes and low speed limits, while roadways and bikeways categorized as LTS 4 are the most stressful and have the highest traffic volumes and speed limits. It is estimated that the majority of current and potential bicyclists find LTS 1 and LTS 2 facilities comfortable.

Within the LTS quality of service measure, a person who identifies as LTS 3 will find LTS 3, LTS 2, and LTS 1 facilities comfortable, a person who identifies as LTS 2 will find LTS 2 and LTS 1 facilities comfortable and so on. If routes are analyzed by LTS, the link or segment with the highest LTS in the route determines the LTS of the entire route, the average LTS of the route does not apply. While, this thesis does not analyze routes, future route-level research should take this into consideration.

The criteria for facilities and intersections are explained in detail below. The criteria matrices follow the rule that the aspect of a link or intersection with the highest LTS determines the LTS of that segment or intersection. For example, a conventional bicycle lane with no adjacent motor vehicle parking (see Table 9) with a street width of one (LTS 1), a posted speed of 35 mph (LTS 3), a functional class of collector (LTS 2), and a traffic volume of 10,000 vehicles per day (LTS 2) would be classified as LTS 3 for the link as a whole. The notation “(no effect)” means that the factor does not cause an increase to that LTS.

The case study was not able to include bicycle through movement at non-signalized intersection LTS, but it will be important to include in future research especially route based analysis and in creating intersection through movement restrictions. Non-signalized intersection LTS is discussed in detail in Chapter 5 Future Research. Left turning bicyclist at signalized intersection criteria is discussed in this section. However, it was not applied to the LTS map (Figure 8). This criteria is also important for route based analysis and should inform left turn restrictions.

Table 6: LTS Roadway and Bikeway Characteristics

LTS Roadway and Bikeway Characteristics	
LTS 1	Considered comfortable and low stress by almost all cyclists. Includes shared paths which separate cyclists from motor vehicle traffic and present few conflict zones such as intersections and driveways. Shared travel lanes are only tolerable if traffic volume is so low that cyclists only occassionally interact with motor vehicles and there is little difference in travel speed between cyclists and motor vehicles due to a posted speed limit of 25 mph or below. Intersections are low stress to approach and cross.
LTS 2	Considered low stress by all cyclists except for people who identify as LTS 1. Includes, side paths and protected cycle tracks which are low stress, but present some conflict zones at driveways and intersections. Shared travel lanes can only have one lane per direction, a speed limit of 30 mph or below, and must be classified as local. Conventional bike lanes and buffered bike lanes allow for slightly higher traffic volume, speed, and classification as local or collector.
LTS 3	Conventional bike lanes or buffered bike lanes are located on roadways with moderate traffic volume and speed and can be classified as minor arterial or lower. Shared travel lanes must be classified as collector or lower and 35 mph or lower. Roadways of LTS 3 can have 2 lanes or less per direction.
LTS 4	Any level of stress beyond LTS 3 excluding limited access roadways. Includes all roadways with a posted speed limit above 40 mph and/or 3 or more lanes per direction with or without bicycle lanes.

3.4 Traffic Stress Criteria for Links

Level of traffic stress was applied to links or segments between intersections for separated, protected, and on street bicycle facilities. The roadway and traffic characteristics which are considered for all roadways and bicycle facility links except for shared-use paths, side paths, and protected cycle tracks are; street width or through lanes per direction, traffic volume of annual average daily traffic (AADT), functional class, and posted speed limit. The focus on traffic volume and speed is supported by Winters' survey of current and potential bicyclists in Metro Vancouver. This study found that high traffic volume and traffic speed were major deterrents from riding [14]. Thus, for conventional bicycle lanes, buffered bicycle lanes, and shared travel lanes, the level of traffic stress for a link increases as those variables increase. The perceived stress caused by the presence of or lack of on street motor vehicle parking was also considered.

3.4.1 On Street Parking

Winters' survey of Metro Vancouver residents found that respondents preferred streets without on street parking to those with on street parking [10]. It would be preferable to consider if the width of the bicycle lane and parking lane were adequate to reduce perceived stress due to the potential of "dooring" (the opening of a motor vehicle's door in the pathway of a bicycle resulting in a collision). However, the case study area lacked data on the width of parking lanes and bicycle lanes and it was assumed that many jurisdictions would lack such data. The case study area also lacked data for on street parking locations and it is likely that very few jurisdictions have this information. On street parking was limited to conventional bike lanes and buffered bike lanes due to the potential that these facilities would position riders in the "dooring" zone. However, future research should incorporate on street parking criteria for shared travel lanes if on street parking data is available.

3.4.2 Street Width (Number of Through Lanes per Direction)

Street width addresses the concern that multilane streets, as opposed to those with one lane in each direction, promote higher motor vehicle traffic speed and decreases the visibility of bicyclists for left-turning and cross motor vehicle traffic at intersections and driveways [1]. The MTI LTS based their LTS criteria for number of lanes on the Dutch CROW Design Manual. MTI LTS modified the Dutch standards by allowing more lanes per direction if the roadway had a median. This study did not consider medians due to the lack of data on the location of medians in the case study area. However, roadways were categorized using the basic street width criteria used by MTI. If jurisdictions have data on the location of medians then the MTI LTS criteria for roadways with medians should be considered. However, further research should be conducted to analyze the preferred lane design of U.S. potential and current bicyclists.

3.4.3 Traffic Volume or Annual Average Daily Traffic (AADT) and Functional Class

MTI LTS does not include traffic volume or functional class when classifying facilities. However, research has shown that the majority of people who want to bicycle more list “too much traffic” as the top environmental barrier [15]. Therefore, traffic volume and functional class were included in this study. Number of travel lanes and functional class have a strong relationship, as the USDOT FHWA Highway Functional Classification Concepts, Criteria and Procedures states, “roadways are designed and constructed according to their expected function” [55]. For example, an arterial is designed to be a high capacity roadway and would likely have more travel lanes, while a collector would likely have less travel lanes than an arterial and a local road even less travel lanes than a collector.

The report notes that the relationship between functional class and number of travel lanes is especially strong in urban areas, which is the intended geographic area of this analysis. USDOT FHWA Highway Functional Classification Concepts, Criteria and Procedures expects roads classified as other principal arterials to have an AADT of 7,000 to 27,000 vehicles per day and minor arterials to have an AADT of 3,000 to 14,000 vehicles per day. However, the expected AADT of major and minor collectors is 1,100 to 6,300 vehicles per day. The AADT of local roads is 80 to 700 vehicles per day [55]. See Figure 7 below for the general relationship between functional class and roadway characteristics, namely AADT and speed limit. For more detailed information on the relationship between functional class and AADT as defined by the USDOT FHWA Highway Functional Classification Concepts, Criteria and Procedures see Appendix B.

Table 7: USDOT FHWA Highway Functional Classification Concepts, Criteria and Procedures

Functional Classification	Distance Served (and Length of Route)	Access Points	Speed Limit	Distance between Routes	Usage (AADT and DVMT)	Significance	Number of Travel Lanes
Arterial	Longest	Few	Highest	Longest	Highest	Statewide	More
Collector	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Local	Shortest	Many	Lowest	Shortest	Lowest	Local	Fewer

[55]

Research by Winters et al also found that when comparing shortest route to actual route (see Figure 4) bicyclists showed a strong preference for routing along bicycle routes and they traveled significantly less along arterial roads than predicted by the shortest route model and significantly more along local roads [33].

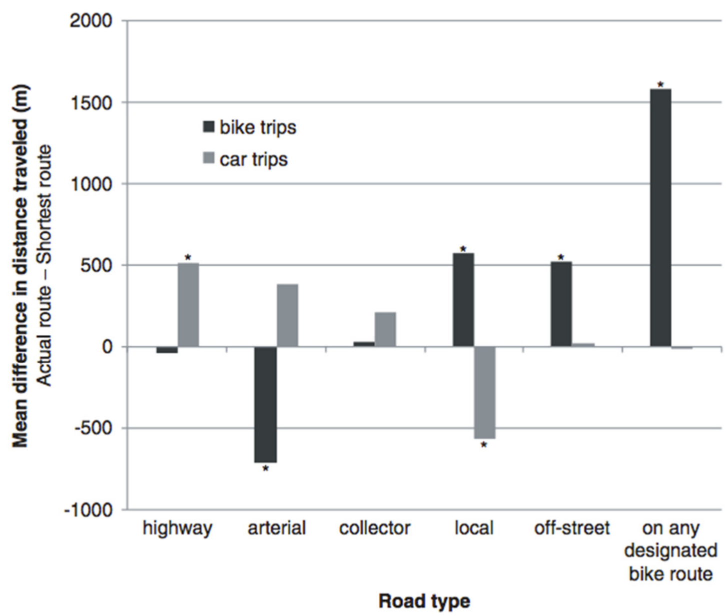


FIGURE 3 Differences in road class usage between actual routes and shortest routes by mode of travel. (Asterisk indicates $p < .05$ in paired t-tests of whether mean difference in distance traveled on road class X between a given actual and shortest route pair is different from 0, for each road class.)

Figure 4: Differences in Road Functional Class Usage Between Actual Routes and Shortest Routes by Mode (Motor Vehicle or Bicycle) [33]

3.4.4 Posted Traffic Speed

High motor vehicle traffic speeds are a deterrent to bicycling. As mentioned in the street width criteria Metro Vancouver current and potential bicyclists rated traffic volume and traffic speeds above 50 km/hr., approximately 30 mph, as major deterrents to riding [14]. Measures of observed speed when available are the best data to use especially when observed traffic speed and the posted speed limit differ. However, observed traffic speed is typically not available. Data on posted speed limit is readily available and for this reason was used in the study. The posted speed limit criteria used in this study follows the methodology used by MTI for conventional bicycle lanes. This study modified the conventional bicycle lane criteria table to create a buffered bicycle lane table since MTI did not include criteria for buffered bicycle lanes in their analysis. The criteria table for buffered bicycle lanes allows for a slighter higher posted speed limit and functional classification, however, the AADT and street width remain the same. Buffered bicycle lane criteria are discussed in further detail later in the chapter.

3.4.5 Criteria for Separated Bicycle Facilities

Separated bicycle facilities or shared-use paths are the most separated from motor vehicle traffic and are classified as LTS 1 due to their potential to meet the perceived level of traffic stress for people who identify as Cycle Atlanta LTS 1 or Interested but Concerned. Protected bicycle facilities such as side paths, one and two-way cycle tracks and raised cycle tracks are classified as LTS 2 due to the potential interaction of motor vehicles and bicycles at mid-block driveways, intersections, and loading bays. These facilities should not exceed the stress tolerance of the Cycle Atlanta LTS 2 of Comfortable but Cautious type.

Winters’ research found that a majority of respondents, both current and potential bicyclists, preferred riding on separated bicycle facilities more than any of the 16 facility designs offered in the survey. Protected cycle tracks were also highly preferred by the majority of respondents in Winters' survey [10]. Winters research also found that a primary deterrent from bicycling for survey respondents was the potential of unsafe interactions with motor vehicles [14]. Other research has shown that people prefer separated bicycle infrastructure [15] [18] [35] [33] [34] [56]. MTI LTS classified all separated bicycle facilities (shared-use paths, side paths, and protected cycle tracks) as LTS 1. However, this method does not consider the potential stress of bicycle and motor vehicle interaction at driveways, intersections, and loading areas.

Table 8: Criteria for Separated Bicycle Facilities

Criteria for Separated and Protected Bicycle Facilities				
	LTS 1	LTS 2	LTS 3	LTS 4
Protected Bicycle Facility (One and Two-Way Cycle Track and Raised Cycle Track)		X		
Sidepath		X		
Shared-Use Path	X			

3.4.6 Criteria for Bicycle Lanes With and Without On Street Parking

The level of traffic stress for roadways with bicycle lanes increases as the street width, posted speed limit, or traffic volume increase. Functional classification of the roadways was also included to validate the other variables. MTI LTS did not consider traffic volume and functional class for conventional bicycle lanes. However, unlike this study, MTI include sum of bike lane and parking lane width and bike lane blockage. Bike lane width and parking lane width were not included in this study since the data was not available for the case study area and would require extensive manual data collection which was not feasible even for the small case study area. However, if a jurisdiction has this data then the MTI LTS criteria for bicycle lane and parking lane width should be referenced. Bicycle lane blockage is discussed in further detail in Chapter 5, Future Research.

The effects of bicycle lanes with color pavement or pavement painted with green paint were not accounted for in this analysis or in the MTI study. Further research should investigate the effect of bicycle lanes with colored pavement on perceived stress as compared to traditional bicycle lanes. However, current and potential bicyclists surveyed in Metro Vancouver did not show a preference for bicycle lanes with a different color pavement than the road, which suggests that green painted lanes alone do not have a significant effect on perceived comfort [14].

Table 9: Criteria for Bicycle Lanes **NOT** Alongside On Street Motor Vehicle Parking

Criteria for Bike Lanes Not Alongside a Parking Lane				
	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (through lanes per direction)	1	(no effect)	≤ 2	(no effect)
Traffic Volume (AADT)	≤ 6,300	> 6,300 - ≤ 14,000	> 14,000 - ≤ 27,000	> 27,000
Functional Class	Local	Major or Minor Collector	Minor Arterial	Principal Arterial
Speed Limit	≤ 25 mph	30 mph	35 mph	≥ 40 mph

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

Table 10: Criteria for Bicycle Lanes Alongside On Street Motor Vehicle Parking

Criteria for Bike Lanes Alongside a Parking Lane				
	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (through lanes per direction)	1	(no effect)	≤ 2	(no effect)
Traffic Volume (AADT)	≤ 3,000	>3,000 - ≤ 6,300	> 6,300 - ≤ 14,000	> 14,000
Functional Class	Local	(no effect)	Major or Minor Collector	Minor Arterial
Speed Limit	≤ 25 mph	30 mph	35 mph	≥ 40 mph

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

3.4.7 Criteria for Buffered Bike Lanes With and Without On Street Parking

Buffered bicycle lanes can have a buffer between the bicycle lane and the through motor vehicle lane and/or between the bicycle lane and the motor vehicle parking lane or curb. This research applies the most importance to the buffer between the bicycle lane and the through motor vehicle lane as it provides a greater separation and allows for slightly higher posted traffic speeds and functional class levels. Research has also shown that unlike the conventional bicycle lane, which almost always places a bicyclist in the “dooring” zone, a buffered bicycle lane with a buffer between the bicycle lane and the parking lane encourages bicyclists to travel outside the “dooring” zone when the through travel lane has appropriate traffic volumes [57] [58].

Future research should consider developing separate LTS criteria tables for buffered bicycle lanes with a buffer only between the through travel lane and the bicycle lane, buffered bicycle lanes with a buffer only between the bicycle lane and the parking lane, and buffered bicycle lanes with buffers between both the through travel lane and bicycle lane and the bicycle lane and the parking lane. There is a lack of research on the perceived stress of these buffered bicycle lane configurations. However, NCHRP Report

766: Recommended Bicycle Lane Widths for Various Roadway Characteristics provides research results on bicyclist positioning in the bicycle lane in response to bicycle lane configuration and traffic volume and may be helpful in developing new criteria tables [58]

Table 11: Criteria for Buffered Bicycle Lanes **NOT** Alongside On Street Motor Vehicle Parking

Criteria for Buffered Bike Lanes Not Alongside a Parking Lane				
	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (through lanes per direction)	1	(no effect)	≤ 2	(no effect)
Traffic Volume (AADT)	≤ 6,300	> 6,300 - ≤ 14,000	> 14,000 - ≤ 27,000	> 27,000
Functional Class	Local or Major or Minor Collector	(no effect)	Minor Arterial	Principal Arterial
Speed Limit	≤ 30 mph	35 mph	≥ 40 mph	(no effect)

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

Table 12: Criteria for Buffered Bicycle Lanes Alongside On Street Motor Vehicle Parking

Criteria for Buffered Bike Lanes Alongside a Parking Lane				
	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (through lanes per direction)	1	(no effect)	≤ 2	(no effect)
Traffic Volume (AADT)	≤ 3,000	>3,000 - ≤ 6,300	> 6,300 - ≤ 14,000	> 14,000
Functional Class	Local	Major or Minor Collector	Minor Arterial	Principal Arterial
Speed Limit	≤ 25 mph	30 mph	35 mph	≥ 40 mph

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

3.4.8 Criteria for Shared Travel Lanes

In this study, the level of traffic stress for bicyclists travelling on shared travel lanes is assumed to be unaffected by signage and shared-lane markings such as sharrows due to a lack of research on markings. Winters found that potential and current bicyclists prefer shared travel lanes with traffic speeds less than 50 kph, approximately 30 mph, which is why roads with speed limits over 30 mph were designated as LTS 3 or 4 in this analysis [14]. Research has also shown that bicyclists prefer roadways with low traffic volume over striped bicycle lanes [35] and avoiding high traffic volume or arterials is one of the most important factors in route choice for bicyclists [33] [35]. Mekuria et al. also note that the Dutch CROW Design Manual does not designate a roadway as acceptable for bicycle accommodation if there is more than one lane per direction [1].

Table 13: LTS Criteria for Shared Travel Lanes with and without On Street Parking

Criteria for Shared Travel Lanes				
	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (through lanes per direction)	1	(no effect)	≤ 2	(no effect)
Traffic Volume (AADT)	≤ 2,000	>2,0000 - ≤ 6,000	> 6,000 - ≤ 14,000	> 14,000
Functional Class	Local	(no effect)	Major or Minor Collector	Minor Arterial
Speed Limit	≤ 25 mph	30 mph	35 mph	≥ 40 mph

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

3.5 Criteria for Signalized Intersections

A signalized intersection criteria matrix was developed for the through movement of bicycles on conventional bicycle lanes, buffered bicycle lanes, and protected cycle tracks with right-turning only motor vehicles lanes. The design scenarios included;

- Through bicycle lane in turning zone (the bicycle facility moves from near the curb to the left of the right-turn only lane)
- Mixing zone (a combined bicycle lane and motor vehicle lane)
- Absence of bicycle-specific infrastructure (the bicycle facility is dropped at the intersection requiring the bicyclists to merge into a shared travel lane)

Signalized separated turning movements for bicycles and motor vehicles and vehicle entry markings were not included in the criteria due to lack of research.

A criteria matrix was also developed for left-turning bicycles at signalized intersections and considered;

- Bike boxes (A designated area at the head of the roadway lane to assist in making bicyclists more visible to motor vehicle traffic. When the bike box extends across all travel lanes for one travel direction, it can assist left-turning bicyclists.)
- Two-stage turn queue boxes (Allow bicyclists to make left turns from a right side bicycle lane or cycle track by proceeding straight through the intersection with the green traffic signal and stopping at a queue box placed in front of motor vehicle traffic on the cross roadway and proceeding through the intersection when the cross roadway traffic signal indicates green.)

[56] [54].

Discussion of criteria for through movement of bicyclists at unsignalized intersections is included in Chapter 5, Future Research. MTI LTS includes criteria for through movement of bicyclists at right-turn only motor vehicle lanes, referred to as pocket bike lanes in the study. The researchers state that they would prefer to use criteria that rely on geometric design measures, however, the data was not available for the case study area and would require extensive manual data collection. MTI simply classified each pocket bike lane as LTS 3. This study gathered information on basic bicycle facility and right-turn only motor vehicle lane configuration though manual observation with Google Earth. This process was time intensive even for the small case study area and may not be feasible in a larger study area.

However, intersection design is a very important component of perceived level of traffic stress for users. Unfortunately, very little research has been conducted on the topic, especially intersection design for protected bicycle facilities. Such facilities offer a reduced potential of bicycle and motor vehicle conflict mid-block, but have the potential of conflict at intersections [56]. Other revealed preference studies have shown that intersection crossings and right and left turns are important for bicyclist route choice [35] [34]. Broach, Dill, and Gliebe's study found that bicyclists preferred intersections without traffic signals or stop signs since they increased delay. However, when traffic volume was moderate or heavy on the crossing street bicyclists in the study preferred traffic signals [35]. The researchers were unsure if the traffic signals decreased delay at busy intersections with few motor vehicle gaps or if the traffic signals increased perceived safety [35].

Further research should be conducted to account for the effects of two-stage turn queue boxes also known as hook turn, box turn, or Copenhagen left. This design assists bicyclists making a left turn at multi-lane signalized intersections when the bicyclist is traveling on a right side conventional bicycle lane, buffered bicycle lane, or protected cycle track [50]. The effects of bike boxes should also be researched as these designated areas at the head of the traffic lane at signalized intersections, often painted green, allow bicyclists to get ahead of queued motor vehicles during the red light phase [50]. Additional intersection criteria should be developed for raised cycle tracks, contraflow lanes, and two-way cycle tracks.

3.5.1 Through Movement of Bicyclist with Motor Vehicle Right Turn Lane

3.5.1.1 Through Bicycle Lane in Turning Zones

Through bicycle lanes are intersection approaches that allow bicyclists in bicycle lanes or protected cycle tracks to position themselves to the left of right-turn only motor vehicle lanes while continuing on a straight path, reducing the potential conflict with right turning motor vehicles [50]. This approach incorporates a turn/merge gap, which is marked with a dotted line to indicate that motor vehicles may enter the bicycle lane at that point [56] [50] [52]. Through bicycle lanes are appropriate to use when a parking lane turns into a right-turn only lane or a right turn bay is created with throat widening of the roadway [52].

The MTI LTS used Dutch criteria for pocket bike lanes, referred to here as through bicycle lanes, to determine intersection LTS for bicycle lanes. An acceptable through bicycle lane design occurs when the right turn lane begins abruptly to the right of the bicycle lane and the geometric design encourages a reduction of right-turning motor vehicle speed through a short turn lane and sharp turning angle. Data is not readily available for geometric design of a roadway, such a turn angle and length of a pocket turn lane. For this reason turn angle was not used in the analysis.

A through bicycle lane was designated as LTS 2 since the facility is designed to reduce the potential for conflict between bicycles and motor vehicles and increase the predictability of bicyclist and motorist movements, however, additional research is needed to verify this classification. The criteria matrix classified the following scenarios at LTS 4 as they were too stressful for the stress tolerance level of most bicyclists; the through travel lane transitions into right-turn-only lane or the bicycle lane is terminated before the intersection. These design configurations may be classified as LTS 3 if the traffic volume and posted speed limit of the roadway is low.

3.5.1.2 Mixing Zones

A mixing zone or combined bike lane and right turn lane is appropriate to use when there is not enough width for a dedicated bicycle lane and turn lane at the intersection. A suggested bicycle lane is located in the far left section of the turn lane and is marked with a dashed line and conventional bicycle stencils [52]. However, shared lane markings or sharrows may also be used [52].

The 2nd Edition of the NACTO Bikeway Design Guide recommends a minimum suggested bicycle lane of four feet with a combined lane width of nine feet minimum and 13 feet maximum, as a lane of more than 14 feet can accommodate both a full motor vehicle turn lane and bicycle lane [52]. The guide also recommends a yield line for motor vehicles in advance of the mixing zone, however, there is little guidance on the length of the mixing zone. More research should be conducted on the design of mixing zones and the effect of mixing zones on bicyclists' LTS. This analysis categorized mixing zones as LTS 3 due to the higher stress that is likely from mixing bicyclists with motor vehicles in the same lane. Bicyclists who can tolerate LTS 3 can ride in mixed traffic, but prefer their own facility.

3.5.1.3 Bike Boxes

Bike boxes designate an area at the head of the traffic lane or lanes at a signalized intersection that allows bicyclists to stop ahead of stopped motor vehicle traffic during the red light signal phase. If the bike box extends across all traffic lanes in one travel direction, the bike box allows bicyclists to safely make a left turn ahead of motor vehicle traffic, especially when exiting a bicycle lane or protected bicycle facility [56] [54]. More commonly, however, bike boxes only extend across one lane of traffic and are intended to reduce “right-hook” conflicts in which a motor vehicle turns right at an intersection and potentially collides with a bicycle in the bicycle lane or protected bicycle facility [59]. Bike boxes are often painted green and are 10 to 16 feet deep with a stop bar to indicate the point where motor vehicles should stop to avoid encroaching upon the bike box [52] [59]. The 2nd Edition of the NACTO Bikeway Design Guide requires that a “No Turn on Red” sign be installed if the city permits right turns on red signal indications [52].

Bike Boxes, referred to as advanced stop boxes or advanced stop lines outside the U.S., have been used for over twenty years in sections of Northern Europe, however, the treatment has only recently been adapted for use in the U.S. [59]. Studies on bike boxes in the U.S. are extremely limited. One 2005 study in Eugene, Oregon was not used in this analysis as the bike box was intended to assist the shift of a bicycle lane from one side of the street to the other at the intersection [60].

A study of ten bike boxes in Portland, Oregon was conducted by Dill et al. from 2008 to 2009 and includes video surveillance of the intersections before and after the installation of the bike boxes and questionnaires of bicyclists and motorists on understanding of the bike boxes and perceived safety [59]. Data from the video surveillance were collected on bicycle and motor vehicle encroachment on the cross walk, motor vehicle encroachment in the bike box during the red signal phase, right-turning motor vehicle encroachment on the bicycle lane before the intersection, the location of the motor vehicle during the red signal phase, and the location of the bicycle in the bike box during the red signal phase [59]. The researchers collected data on motor vehicle and bicycle conflicts and yielding before and after the installation of the bike boxes. The survey of motorists indicated that 84% of respondents understood the purpose of the bike box, “increasing visibility of cyclists, increasing safety, having cars stop back or bike go ahead, minimizing conflict of right-hook, etc.,” and 94% chose the correct stopping location for a motor vehicle at a red signal phase, stopping before the bike box [61]. These results show that bike boxes are not an expectancy issue for motorists.

Before and after comparisons of intersections without and with bike boxes showed similar rates of motor vehicle encroachment on crosswalk, 23.2%, and on bike boxes, 26.8%, which illustrates that motorists understand the stopping expectation of bike boxes [61]. The researchers observed an increase in right-turning motorists yielding to bicyclists when comparing the intersection before and after the bike box treatment was installed. The bike boxes increased the perception of safety to bicyclists with 77% of surveyed respondents indicating that the bike box made the intersection safer for them as a bicyclist and 81% indicating that they thought motorists were more aware of bicyclists because of the bike box treatment [61]. Data collected from the video surveillance of motor vehicle encroachment on bicycle lanes leading to intersections with bike boxes gave mixed results. Motor vehicle encroachments on the bicycle lane stopped for the red signal phase decreased, however, the proportion of motor vehicles encroaching on the bicycle lane in advance of turning right increased at intersections with a bike box [61].

Additional research needs to be conducted on intersection design especially for protected bicycle facilities [62]. The researchers focused on “right-hook” conflicts and found that bicyclists were more likely to use the bicycle lane to approach the intersection instead of queuing in motor vehicle traffic and more likely to stop before the crosswalk after the bike box was installed. The researchers observed conflicting data on stop line encroachment by motor vehicles at the two intersections before and after bike box installation so no conclusions could be drawn. Researchers also found mixed results of non-compliance of right-turning motor vehicles obeying the “No Right Turn on Red” sign. At one intersection, 79% of right-turning vehicles turned right illegally, yet only 5.3% of motorists at the other intersection made illegal right turns [62].

While, there is not extensive research on bike boxes reducing perceived stress especially the stress of "right hooks" by motor vehicles, it is important to include bike boxes as a perceived level of traffic stress criteria. For this reason bike boxes which extend across one traffic lane were categorized as LTS 2 for this analysis as the bike box separates bicyclists from motor vehicle traffic.

Table 14: Level of Traffic Stress for Signalized Intersections: Through Bicycle Movement with Right-turning Only Motor Vehicle Lane

Level of Traffic Stress for Signalized Intersections: Through Bicycle Movement with Right-turning Only Motor Vehicle Lane	
Facility Design	**LTS**
Through Bike Lane: A bicycle lane which moves from near the right curb to the left of the right-turn lane, which is created when a parking lane becomes a turn lane or a right-turn bay is created with throat widening of the roadway. Through bicycle lanes are intersection approaches that allow bicyclists in bicycle lanes or protected bicycle facilities to position themselves to the left of right-turn lanes while continuing on a straight path and should have a minimum width of 4 feet and a desired width of 6 feet. The approach includes a turn/merge gap, which is marked with a dotted line to indicate that motor vehicles may enter the bicycle lane at that point [1] [20] [48].	LTS ≥ 2
Bike Box (one traffic lane): A designated area located at the head of a traffic lane typically painted green which is 10 to 15 deep and extends across one traffic lane, which places bicycles ahead of motor vehicles at signalized intersection during the red signal phase. The most common application of the bike box places bicycles in from of right-turning motor vehicles to reduce "right-hook" conflicts [61].	LTS ≥ 2
Mixing Zone: Single right-turn bay, which begins abruptly, but requires a combined bicycle lane/motor vehicle turn lane.	LTS ≥ 3
Through lane becomes a right-turn only lane	LTS ≥ 4
No bicycle infrastructure: A conventional bicycle lane or protected facility along the link, which is dropped at the intersection resulting in no bicycle specific accommodations at the intersection.	LTS ≥ 4
Shared travel lane with no bicycle infrastructure: A shared travel lane along the link that has no bicycle specific accommodations at the intersection.	(no effect)

3.5.2 Left-turning Bicyclist at Signalized Intersection

3.5.2.1 Bike Box

Bike boxes were discussed extensively in this report as a design treatment to reduce bicycle and motor vehicle conflicts at signalized intersections when motor vehicles are turning right. The previous study on bike boxes that analyzed ten intersections in Portland, Oregon was the study found [61]. However, none of the ten intersections were designed to assist left-turning bicyclists and signalized intersections. All of the bike box treatments were confined to one travel lane and did not extend across all traffic lanes for one travel direction as required to assist left-turning vehicles.

This design application is applied in this thesis with some reservation due to lack of research in the U.S., however, the use of bike boxes which extend across all traffic lanes in one travel direction to assist left-turning bicyclists at signalized intersections represents one of only two designs to assist left-turning bicyclists at intersections. The use of bike boxes should be reassessed as additional research is conducted. However, this analysis classified bicycle boxes as LTS 2, since bike boxes separate bicyclists from motor vehicle traffic.

3.5.2.2 Two-Stage Turn Queue Box

Two-stage turn queue boxes can be installed at signalized intersections and allow bicyclists to make left turns from a right side conventional bicycle lane, buffered bicycle lane, or protected cycle track by proceeding straight through the intersection with the green traffic signal illustrated as phase 1 in Figure 5, cyclists then stop at a queue box placed in front of motor vehicle traffic on the cross roadway which is illustrated as phase 2 in the figure and cyclists then proceed through the intersection when the cross roadway traffic signal indicates green to complete the maneuver as seen in phase 3 in the figure.

The queue box is often painted green and located in front of the pedestrian crosswalk. The queue box should be positioned in front of the cross street travel lane, however, if there is a bicycle facility across the intersection the queue box can be positioned in front of the cross street parking lane. As with bike boxes, it is recommended that a “No Turn on Red” sign should be installed if the city permits right turns on red signal indications [52].

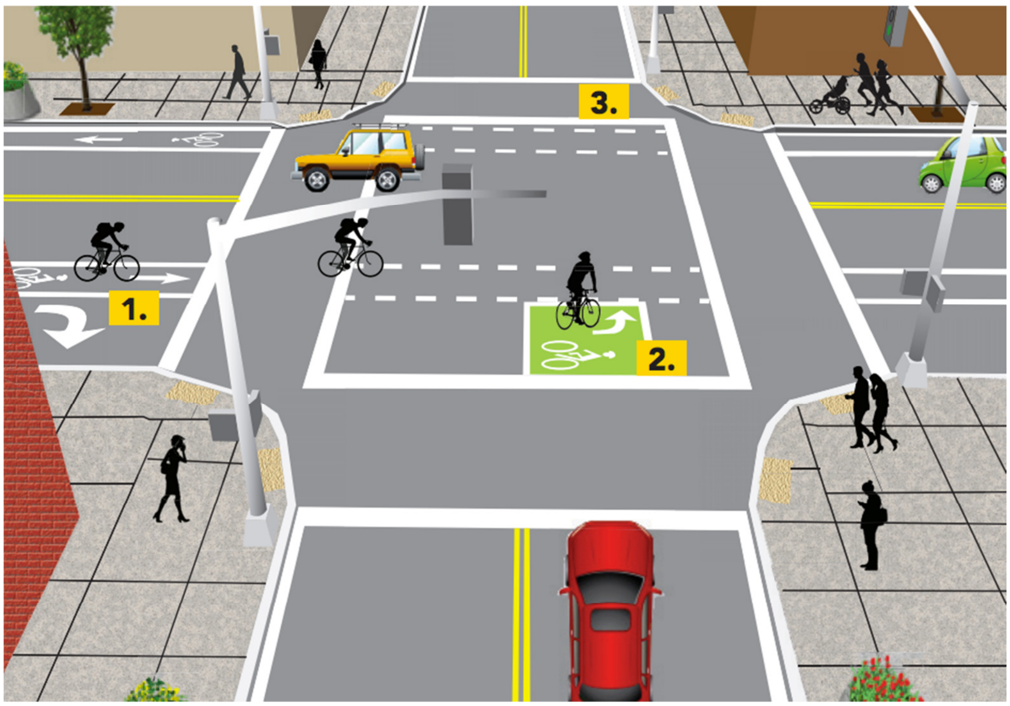


Figure 5: Two-Stage Turn Queue Box [54]

Only one study could be located on the two-stage turn queue box also referred to as a Copenhagen Left. However, the study focused on developing a model to assess the impacts of a Copenhagen Left as compared to diagonal left-turns by bicyclists on reducing impedance to motor vehicles and increasing motor vehicle capacity, while analyzing the delay impacts of Copenhagen Left on bicyclists [63]. The study did not focus on perceived safety, which would be most useful in assigning a level of traffic stress to the two-state turn queue box. However, the researchers were able to draw some interesting observations from the video surveillance of bicyclists in China that they used to inform their model. Importantly, bicyclists were observed performing a Copenhagen Left at an intersection with high traffic volume and a large number of traffic lanes even if there was not a Copenhagen Left installed at the intersection. Conversely, bicyclists were observed not using installed Copenhagen Left at intersections with low traffic volume and few lanes [63]. These observations should be studied further to determine the traffic volume and number of lanes that makes a Copenhagen Left optimal in aiding left-turning bicyclists.

Table 15: Criteria for Left-turn Bicycle Facilities at Signalized Intersections

Level of Traffic Stress for Signalized Intersections: Left-turning Bicycles	
Facility Design	Level of Traffic Stress
Bike Box (extending across all traffic lanes in one travel direction): A designated area located at the head of a traffic lane typically painted green which is 10 to 15 deep and extends across all traffic lanes in one travel direction, which places bicycles ahead of motor vehicles at signalized intersection during the red signal phase. A bike box which extends across all traffic lanes in one travel direction allows a bicyclists to make a left turn ahead of motor vehicle traffic, especially when exiting a bicycle lane or protected bicycle facility [56] [54].	LTS ≥ 2
Two-Stage Turn Queue Box: Installed at signalized intersections and allows bicyclists to make left turns from a right side bicycle lane or cycle track by proceeding straight through the intersection with the green traffic signal and stopping at a queue box placed in front of motor vehicle traffic on the cross roadway and proceeding through the intersection when the cross roadway traffic signal indicates green.	LTS ≥ 2
No bicycle infrastructure: A conventional bicycle lane or protected facility along the link without a left-turn bicycle facility at the intersection.	LTS ≥ 3
Shared travel lane with no bicycle infrastructure: A shared travel lane along the link that has no bicycle specific accommodations at the intersection.	(no effect)

3.6 Criteria for Unsignalized Intersections

3.6.1 Bicycle Through Movement at Unsignalized Intersections

Separated paths and protected bicycle facilities are separated from most motor vehicle traffic except at intersections or crossings. The point for greatest potential motor vehicle and bicycle conflict for separated paths is when the path must cross a roadway or when a path terminates at an intersection. Bicyclists traveling on a protected bicycle facility, bicycle lane, or shared travel lane are also likely to experience elevated perceived stress at unsignalized intersections especially when the roadway being crossed has multiple lanes and a higher posted speed limit. The criteria for unsignalized crossings in Table 16 and Table 17. The criteria tables for unsignalized crossings are modified versions of the MTI LTS criteria tables.

It is important to include the perceived stress of bicycle through movement at unsignalized intersections. However, the application of the criteria for unsignalized crossings in the case study area was limited (see Figure 11) since the criteria had to be applied manually. Future research that includes a larger study area or analysis of a bikeshed including LTS 3 would require the criteria for unsignalized crossing to be applied through a program. The MTI research on LTS applied their criteria for unsignalized crossings using a program.

Future research should also consider the inclusion of AADT or traffic volume in the criteria table for unsignalized crossings. The inclusion of AADT is important when the traffic volume is so high that gaps in motor vehicle traffic are rare, causing crossing by the bicyclist to be delayed and potentially increasing the perceived stress of the crossing. There is potential to model the AADT criteria off of the 2009 MUTCD Section 4C.05 Warrant 4. Pedestrian Volume which evaluates the need for a traffic control signal at an intersection or midblock crossing, "where the traffic volume of a major street is so heavy that pedestrians experience excessive delay in crossing the major street" [64]. Future research should also consider expanding the criteria table for unsignalized crossing to consider if the crossing street has a pedestrian refuge island. The criteria tables for unsignalized crossings with consideration of medians are discussed in Chapter 5 Future Research.

Table 16: Criteria for Unsignalized Intersections with Bicyclist Through Movement

Criteria for Unsignalized Crossings				
		Street Width		
		≤ 3 lanes	4 - 6 lanes	> 6 lanes
Speed Limit	≤ 25 mph	LTS 1	LTS 2	LTS 4
	30 mph	LTS 2	LTS 2	LTS 4
	35 mph	LTS 2	LTS 3	LTS 4
	≥ 40 mph	LTS 3	LTS 4	LTS 4
Note: number of lanes refers to entire street				

Table 17: Alternative Criteria for Unsignalized Intersections with Bicyclist Through Movement

Alternative Criteria for Unsignalized Crossings			
		Street Width	
		≤ 3 lanes	≥ 4 lanes
Speed Limit	≤ 30 mph	LTS 2	LTS 3
	31 - 40 mph	LTS 3	LTS 3
	≥ 40 mph	LTS 4	LTS 4
Note: number of lanes refers to entire street			

CHAPTER 4

CASE STUDY

The Atlanta BeltLine Eastside trail is a small part of a much larger transportation and economic development project which will provide parks, shared use paths and transit along a 22-mile historic railroad corridor in Atlanta, Georgia [53]. See Figure 6 below to see a section of the Eastside Trail before and after the shared use path was built. The completed Atlanta BeltLine will connect 45 neighborhoods. Four sections of the trail are currently completed and the Eastside Trail, which is the focus of this case study was the first segment to be completed [53]. Figure 7 shows the entire Atlanta BeltLine in green with the completed Eastside Trail in blue and the roadway network which the LTS quality of service measure is applied to in grey.

Figure 6: Atlanta BeltLine Eastside Trail Before and After [65]

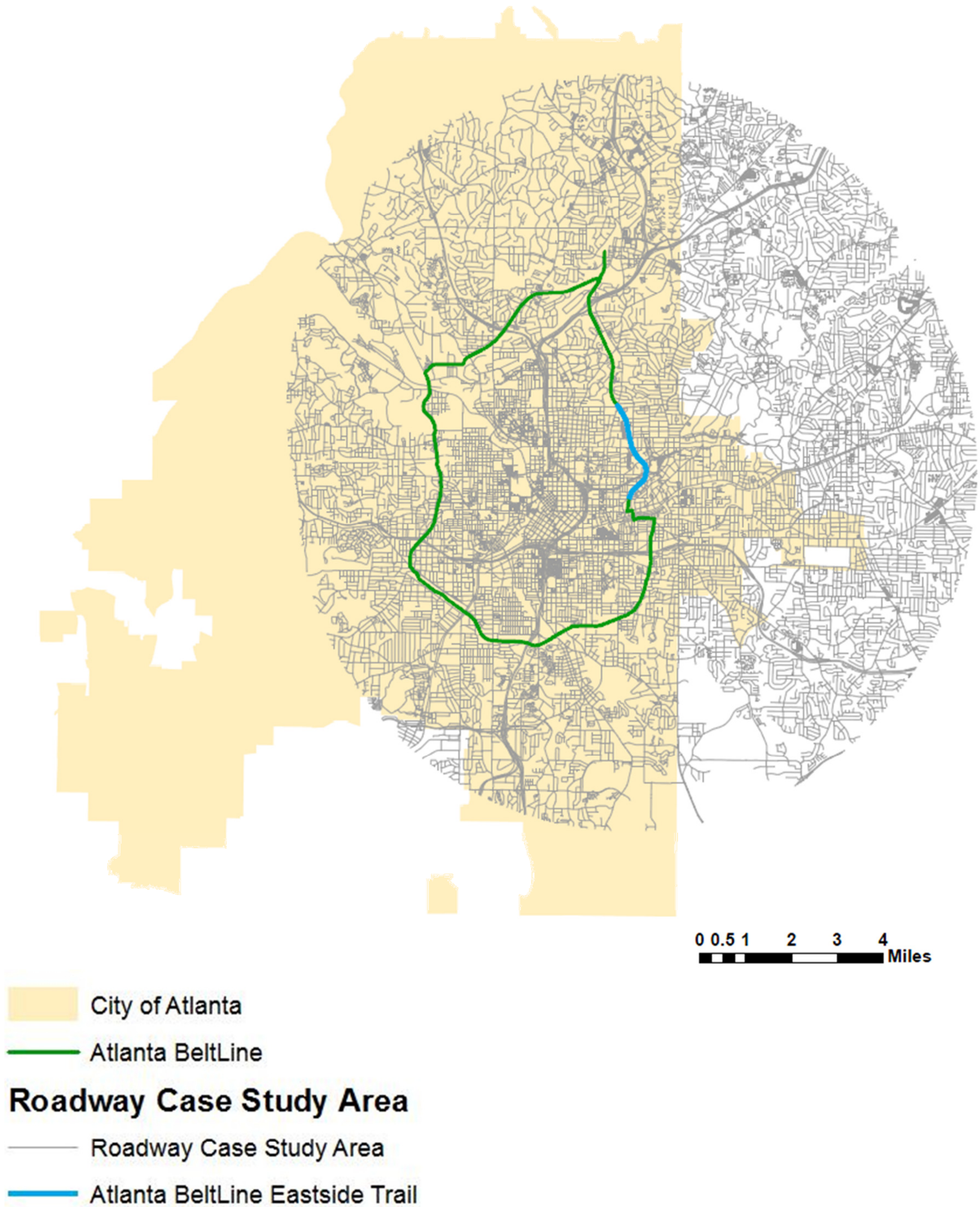


Figure 7: Case Study Area, Six-Mile Buffer around the Atlanta BeltLine Eastside Trail

The case study area was limited to a six-mile buffer around the Eastside Trail as research has shown that routes over six miles are perceived as a strong deterrent in the choice to bicycle for many people [14]. The distance that a person can bicycle from the

Eastside Trail outward on roadway and bikeways, also referred to as a bikeshed, is analyzed in the case study at LTS 1 and LTS 2 with and without unsignalized crossing criteria applied. It is assumed that the majority of bicyclists would not tolerate traveling more than six miles from the Eastside Trail.

4.1 Data

Three primary data sources were used in this analysis. The NAVTEQ Streets 2014 shapefile was obtained by Atlanta Regional Commission (ARC) from the company HERE. The shapefile had the most accurate geographic information on roadways in the study area of the data available to the researcher. It includes a comprehensive inventory of roadways, especially local roadways which are omitted from other data sources. The other roadway database used in the research, RC_ROUTES_ARC, is a modified version of the roadway database maintained by the Georgia Department of Transportation (GDOT) and focuses on state managed roadways rather than locally managed roadways and bikeways. The third primary data source was the Metro Atlanta Bicycle Facility Inventory, which the researcher compiled from information provided by local governments in the region and verified with Google Earth and Bing Imagery.

Using ArcGIS 10.2, the attribute table information from RC_ROUTES_ARC and Metro Atlanta Bicycle Facility Inventory were transferred to the NAVTEQ Streets 2014 shapefile. Since RC_ROUTES_ARC and NAVTEQ Streets 2014 did not have any common fields in their attribute tables, the RC_ROUTES_ARC attribute information had to be transferred to NAVTEQ Streets 2014 through a manual process which took approximately 40 hours. This manual method would not be efficient in a larger study area. While the transfer of information was time consuming it was important to include the NAVTEQ Streets 2014 roadway geographic information due to the inclusion of local roadways which play an important role in building a connected bicycle network which the majority of current and potential bicyclists would be comfortable riding. The 2014 version of NAVTEQ is the first version to include bicycle and pedestrian facilities [66], however, any shared use paths or side paths which were not included in NAVTEQ Streets 2014 were added by merging the Metro Atlanta Bicycle Facility Inventory.

Table 18: Data Sources Used in Case Study Area

Data	Source	Field	Alternative Source	Alternative Field
Road Facilities	NAVTEQ Streets 2014	NA	NA	NA
Bike Facilities	Metro Atlanta Bicycle Facility Inventory	FACTYPE1	NA	NA
Street width (through lanes per direction)	RC_ROUTES_ARC	T_LANES LE & T_LANES_RI	NAVTEQ Streets 2014	LANE_CAT
Traffic Volume (AADT)	RC_ROUTES_ARC	AADT	NAVTEQ Streets 2014	NA
Functional Class	RC_ROUTES_ARC	S_FUNCLASS	NAVTEQ Streets 2014	FUNC_CLASS
Posted Speed Limit	RC_ROUTES_ARC	SPEED_LIMI	NAVTEQ Streets 2014	SPEED_CAT

The location of on street parking on roadways with conventional bicycle lanes and buffered bicycle lanes was manually coded in ArcGIS by the researcher using Google Earth imagery. The treatment of intersection approaches with right turn only motor vehicle lanes that connect to links with conventional bicycle lanes, buffered bicycle lanes, or protected cycle tracks were also manually coded in ArcGIS using Google Earth Imagery. Bike boxes which were not included in the original Metro Atlanta Bicycle Facility Inventory file were also added during this process. It was too time consuming even in the case study's small geographic area to gather on street parking data for shared travel lanes.

4.2 Results

An overview of the case study area with link and right-turn only motor vehicle lane LTS applied can be seen below in Figure 8. Criteria for left-turning bicyclist at signalized intersections and criteria for bicycle through movement at unsignalized intersections are excluded from this map. LTS is coded by color with blue = LTS 1, green = LTS 2, orange = LTS 3, red = LTS 4 and grey indicating limited access roadways. The map has a limited number of roadways and bikeways coded blue or LTS 1, however, a large portion of the map has green or LTS 2 roadways and bikeways. The prevalence of LTS 2 facilities was also noted in the MTI study and indicates the prevalence of local or neighborhood streets in the case study area [1]. Table 19 presents the distribution of centerline miles of roadway and bikeway LTS. Over half of the centerline miles in the case study area are coded as LTS 2, however further analysis of connectivity should be conducted to determine if these LTS 2 facilities created a connected bicycle network. Connectivity analysis was not conducted in this thesis. Instead an analysis of the bikeshed of the Atlanta BeltLine Eastside Trail for LTS 1 and LTS 2 facilities was completed. A bikeshed is the distance that a bicyclist can travel from a given point outward, in this case the Atlanta BeltLine Eastside Trail.

Table 19: Distribution of Centerline Miles by Level of Traffic Stress

Distribution of Centerline Miles by LTS

	Conventional Bicycle Lanes	Buffered Bicycle Lanes	Shared Travel Lanes	Side Paths	Protected Cycle Tracks	Shared Use Paths	Limited Access	Total	Percent
LTS 1	0	0	317.2	0	0	26.7	0	343.9	15.2%
LTS 2	5.5	0.1	1206.4	10.3	0.9	0	0	1223.2	54.0%
LTS 3	20.6	0.2	249.1	0	0	0	0	269.9	11.9%
LTS 4	8.9	1.4	255.2	0	0	0	0	265.5	11.7%
NA	0	0	0	0	0	0	164.1	164.1	7.2%
Total	35	1.7	2027.9	10.3	0.9	26.7	164.1	2266.6	100.0%

Figure 9 presents a zoomed-in version of Figure 8 to provide a more detailed image of the LTS classification of roadways and bikeways around the Atlanta BeltLine Eastside Trail.

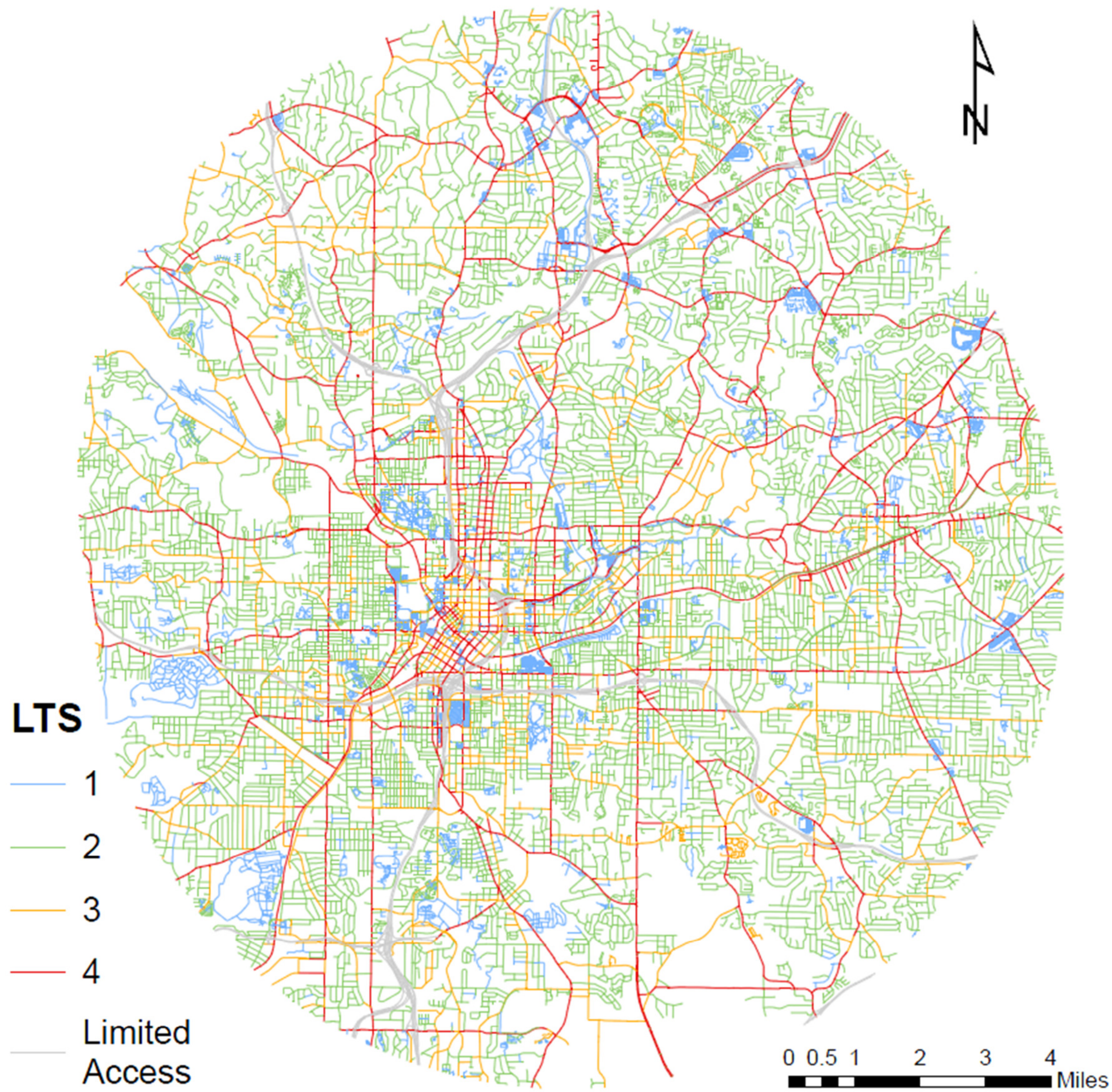


Figure 8: Link and Right-turn Only Lane LTS in Case Study Area

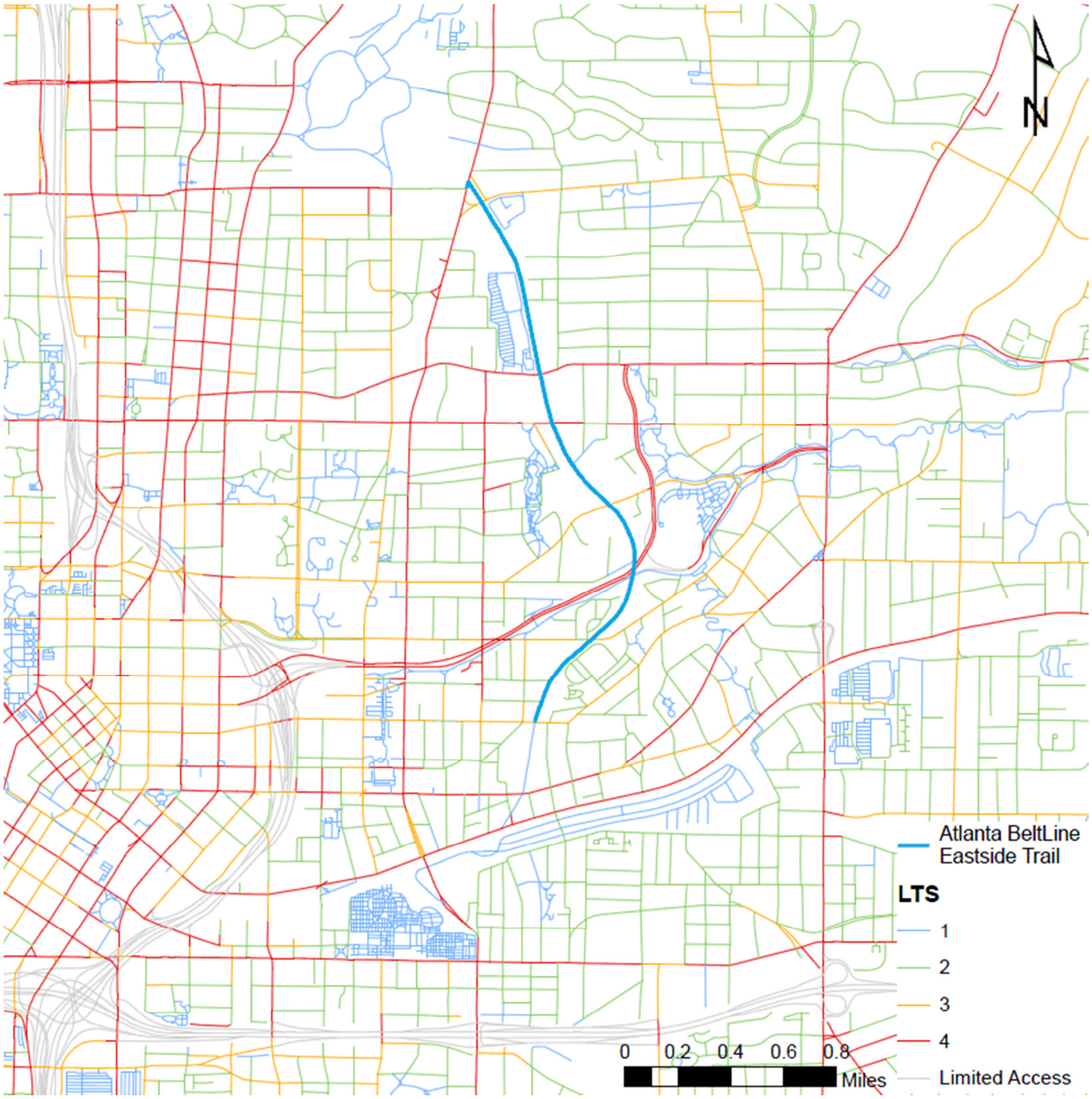


Figure 9: Closer View of LTS in Case Study Area

A map of roadways and bikeways classified as LTS 1 or LTS 2 is shown in Figure 10. This map reveals that while a majority of the roadways and bikeways in the study area are classified as LTS 1 and LTS 2, these facilities appear to not be well connected. This concept is explored further in the map in Figure 11 where the Atlanta BeltLine Eastside Trail's bikeshed is considered for LTS 1 and LTS 2 facilities.

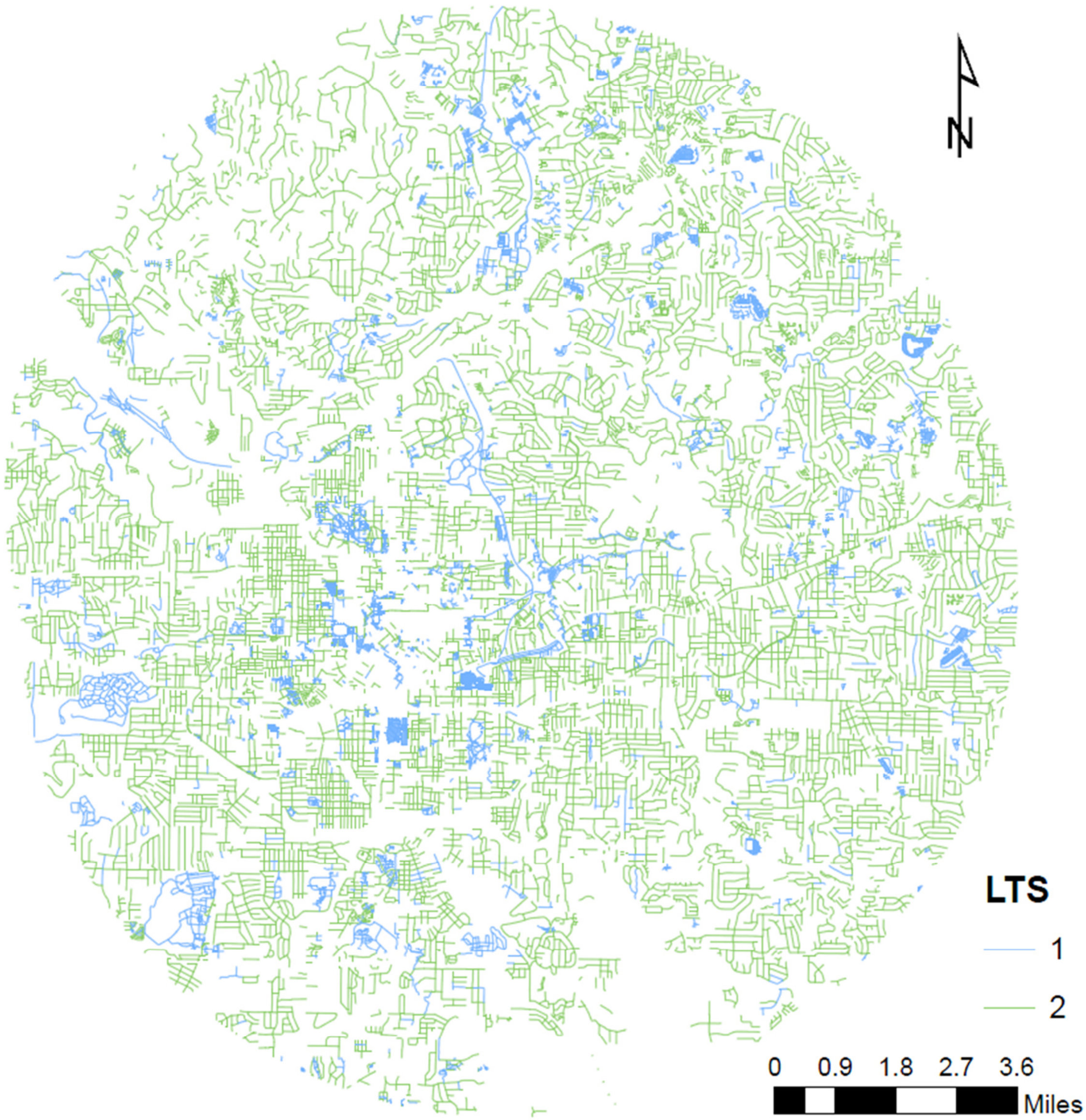


Figure 10: Case Study Area LTS 1 and LTS 2 Facilities Only

The overview map, Figure 11, shows that the bikeshed does not spread very far outward and includes gaps within the bikeshed. Figure 12 shows a closer view of the previous map. While Figure 13 includes City of Atlanta Neighborhood Planning Units (NPU) E, F, M, N, and W on the bikeshed map. NPU E includes the neighborhoods of

Ansley Park, Ardmore, Atlantic Station, Brookwood Hills, Georgia Tech, Home Park, Loring Heights, Marietta Street Artery, Midtown, and Sherwood Forest. NPU F includes Atkins Park, Lindridge/Martin Manor, Morningside/Lenox Park, Piedmont Heights, Virginia Highland. NPU M includes Castleberry Hill, Downtown, and Old Fourth Ward. NPU N includes the neighborhoods of Cabbagetown, Candler Park, Druid Hills, Inman Park, Lake Clair, Poncey-Highland, and Reynoldstown. While NPU W includes Benteen Park, Boulevard Heights, Custer/McDonough/Guice, East Atlanta, Grant Park, Oakland, Ormewood Park, State Facility, and Woodland Hills.

The majority of NPU E, M, and W are not reached by the Eastside Trail LTS 1 and LTS 2 bikeshed. As discussed in Chapter 2, Literature Review/Background, university students are more likely to bicycle than other demographics. Georgia State University (GSU) is located in downtown Atlanta. The potential for the mode share of trips within and to and from downtown Atlanta by GSU students has potential to increase if low stress infrastructure is installed. NPU M includes both the Georgia Institute of Technology campus. Like NPU E, this area has the potential to see increased bicycling mode share due to the concentration of students.

Midtown and Downtown Atlanta (NPU E and NPU M) both have a high density of employers, while, NPU F, N, and W primarily consists of residential neighborhoods. As can be seen in Figure 13, NPU F and N have higher coverage by the Eastside BeltLine LTS 1 and LTS 2 Bikeshed. There is the potential to increase home to work trips by bicycle if these neighborhoods can be better connected by low stress facilities, particularly to Downtown and Midtown.

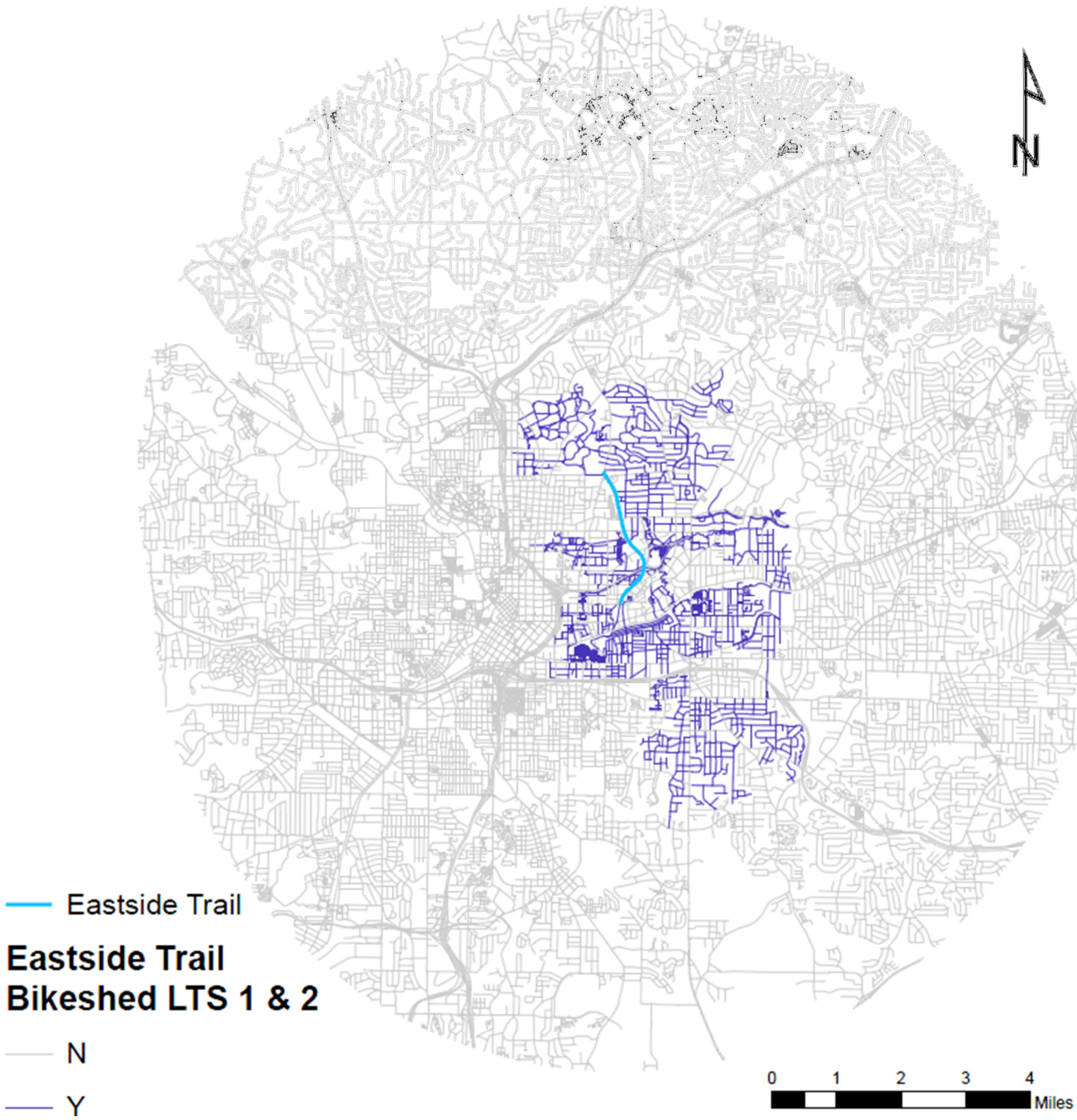


Figure 11: Eastside Trail Bikeshed with LTS 1 and LTS 2 Facilities Only

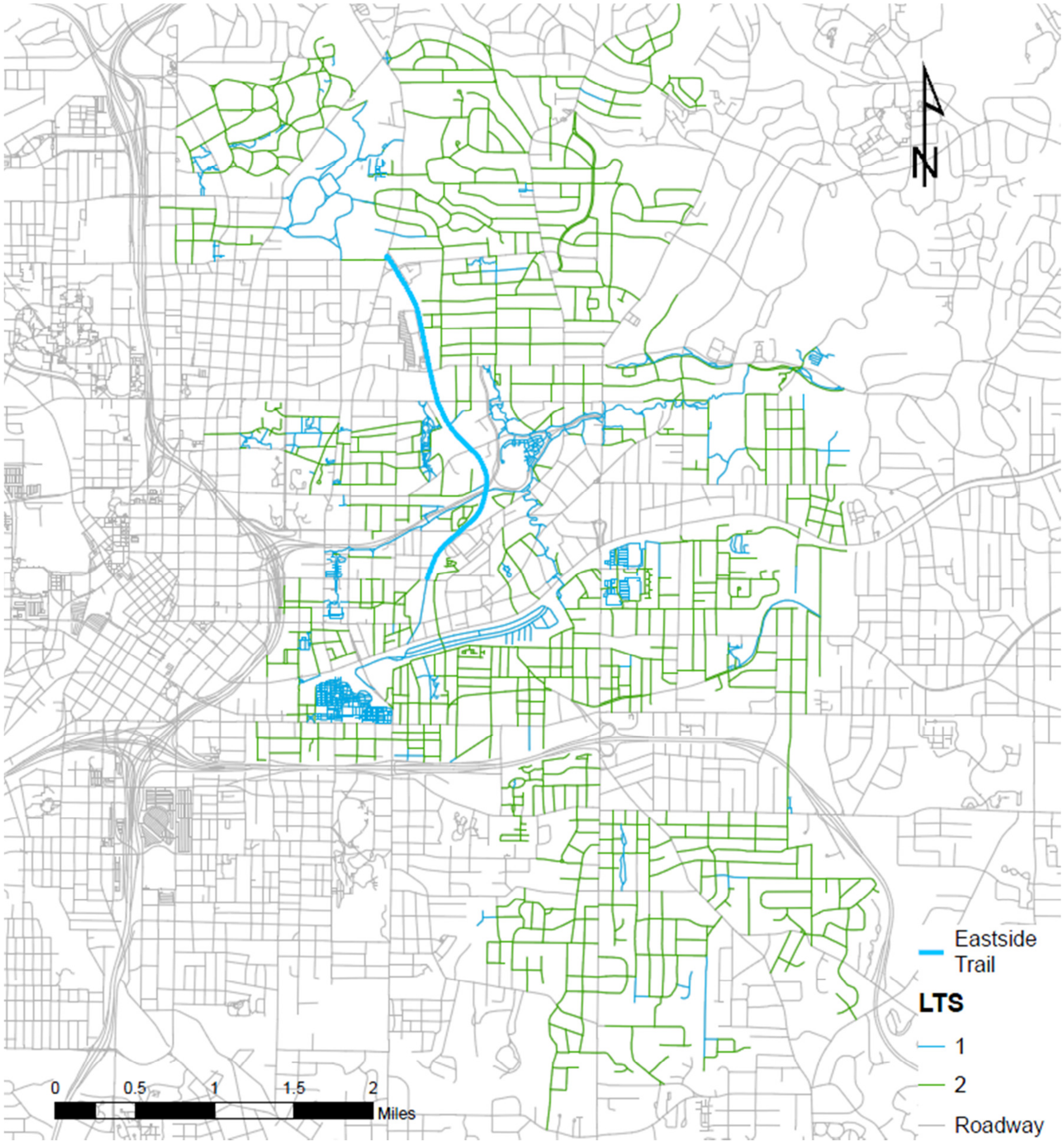


Figure 12: Closer View of Eastside Trail Bikeshed with LTS 1 and LTS 2 Facilities Only

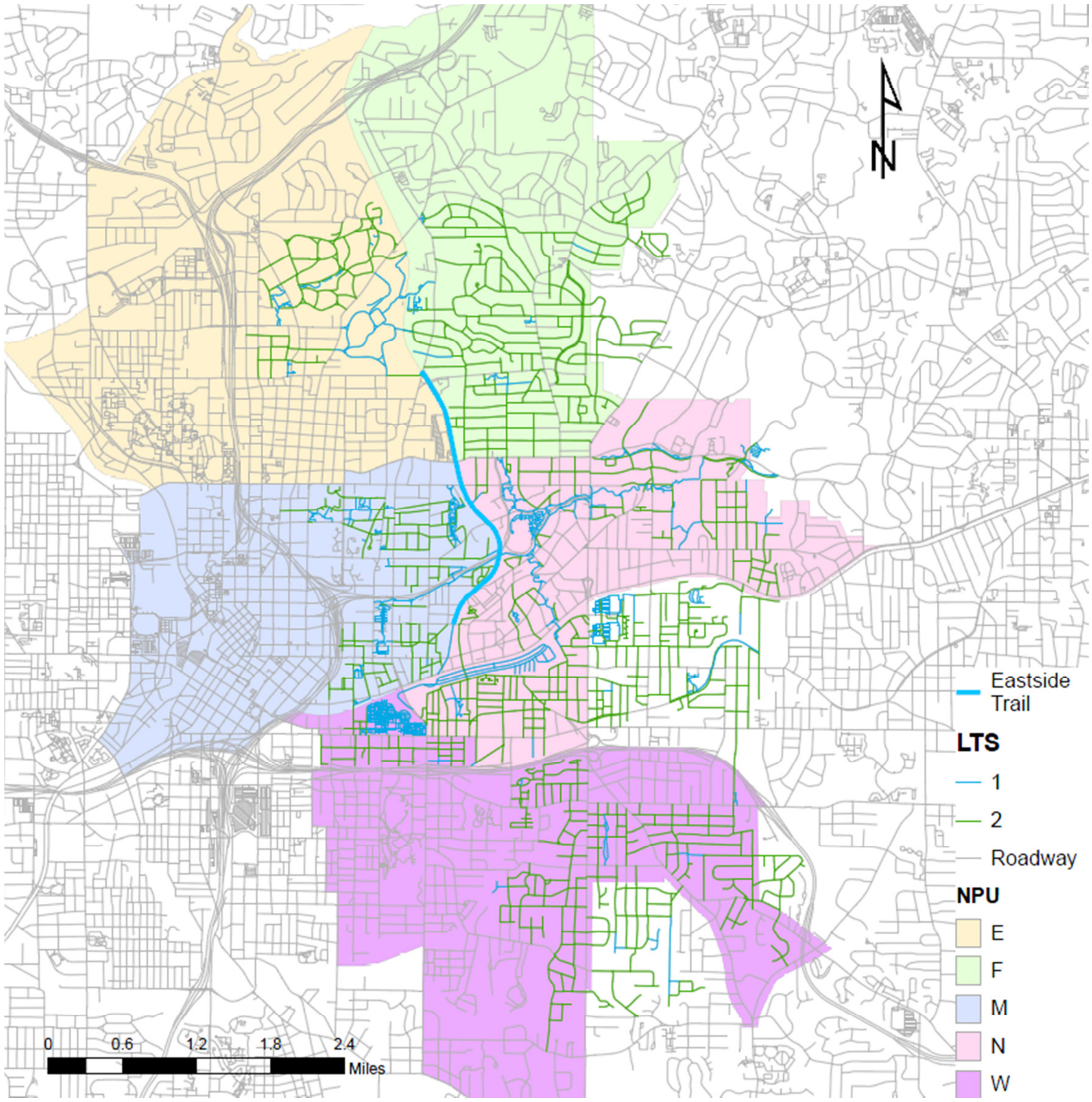


Figure 13: Eastside Trail Bikeshed at LTS 1 and LTS 2 with NPU

The previous bike shed analysis did not include unsignalized intersection crossing LTS criteria. The LTS 1 and LTS 2 bikeshed for the Atlanta BeltLine Eastside Trail was reanalyzed using unsignalized intersection crossing criteria. Figure 14 compares the bikeshed with and without this criteria applied. The dark grey facilities are those that were included in Figure 12-14, but which were excluded in Figure 14 due to the presence of unsignalized intersections which exceeded LTS 1 and LTS 2 criteria. Figure 15 shows a closer view of the excluded facilities in the north eastern portion of the bikeshed. Several unsignalized intersections along Piedmont Avenue prevented these facilities from being included in the bikeshed. While there is a signalized intersection at The Prado NE and Piedmont Avenue the bikeshed is stopped due to small section of roadway The Prado NE which is classified as higher than LTS 2 due to a bicycle lane which is dropped at an intersection with a right-turn only motor vehicle lane. This neighborhood could be included in the Eastside Trail LTS 1 and LTS 2 Bikeshed with the installation of a through bicycle lane at the right-turn only lane.

A closer view of another section of the bikeshed that is excluded when unsignalized intersection crossing LTS criteria is applied can be seen in Figure 16. This map focuses on the southern portion of the bikeshed and includes numerous facilities that were excluded from the bikeshed due to unsignalized intersection crossings at Moreland Avenue which exceeded LTS 2. Moreland Avenue is a major roadway and presents a barrier for bicyclists trying to cross at unsignalized intersections. The bikeshed could extend across Moreland Avenue in this area if a traffic signal or Pedestrian Hybrid Beacon is installed to reduce the stress of crossing.

The finding that the low stress bicycle network is impeded by major roadways as cross streets at unsignalized intersections is also supported by the MTI study. It is important that future research, especially route analysis, develops a program to analyze unsignalized intersection crossing LTS criteria.

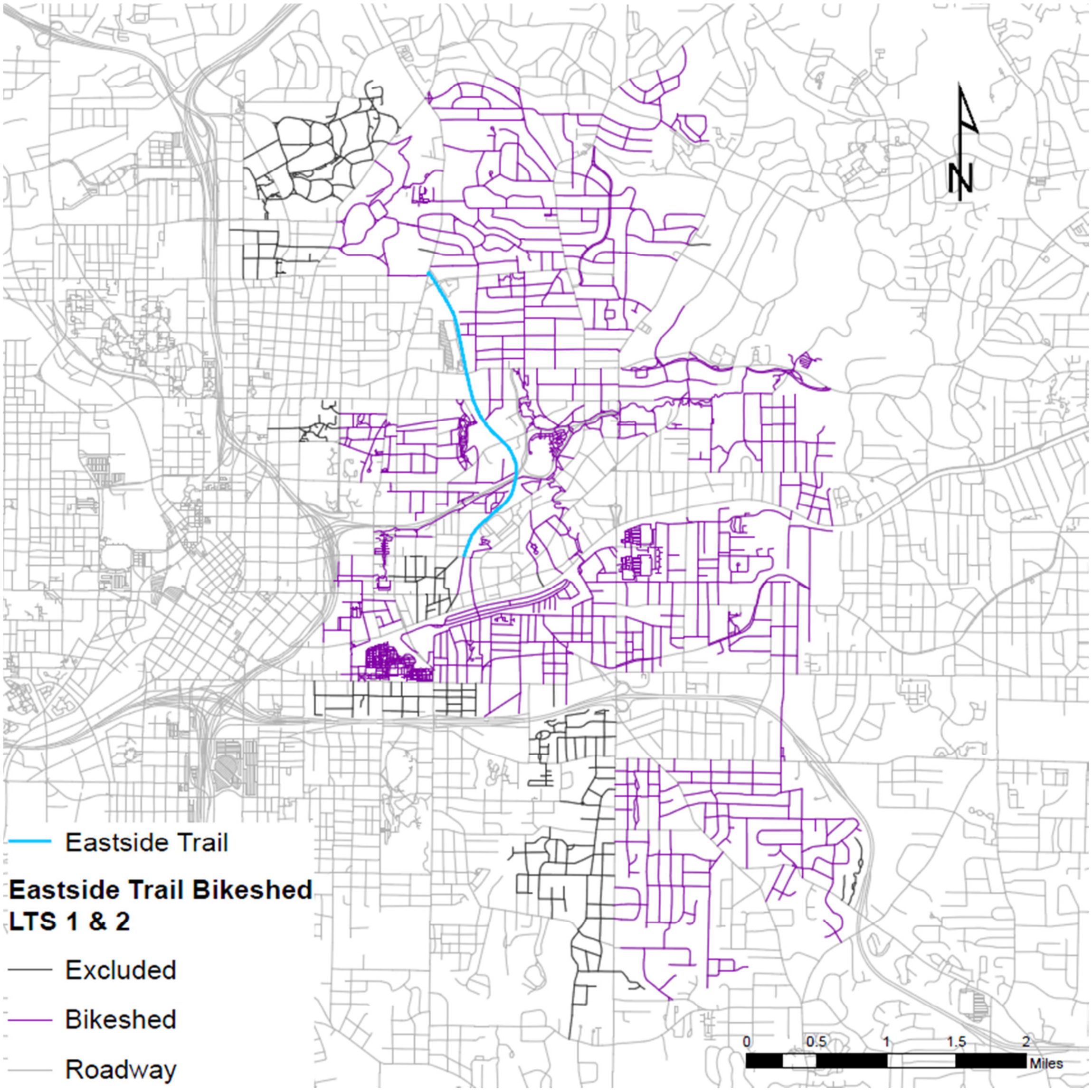
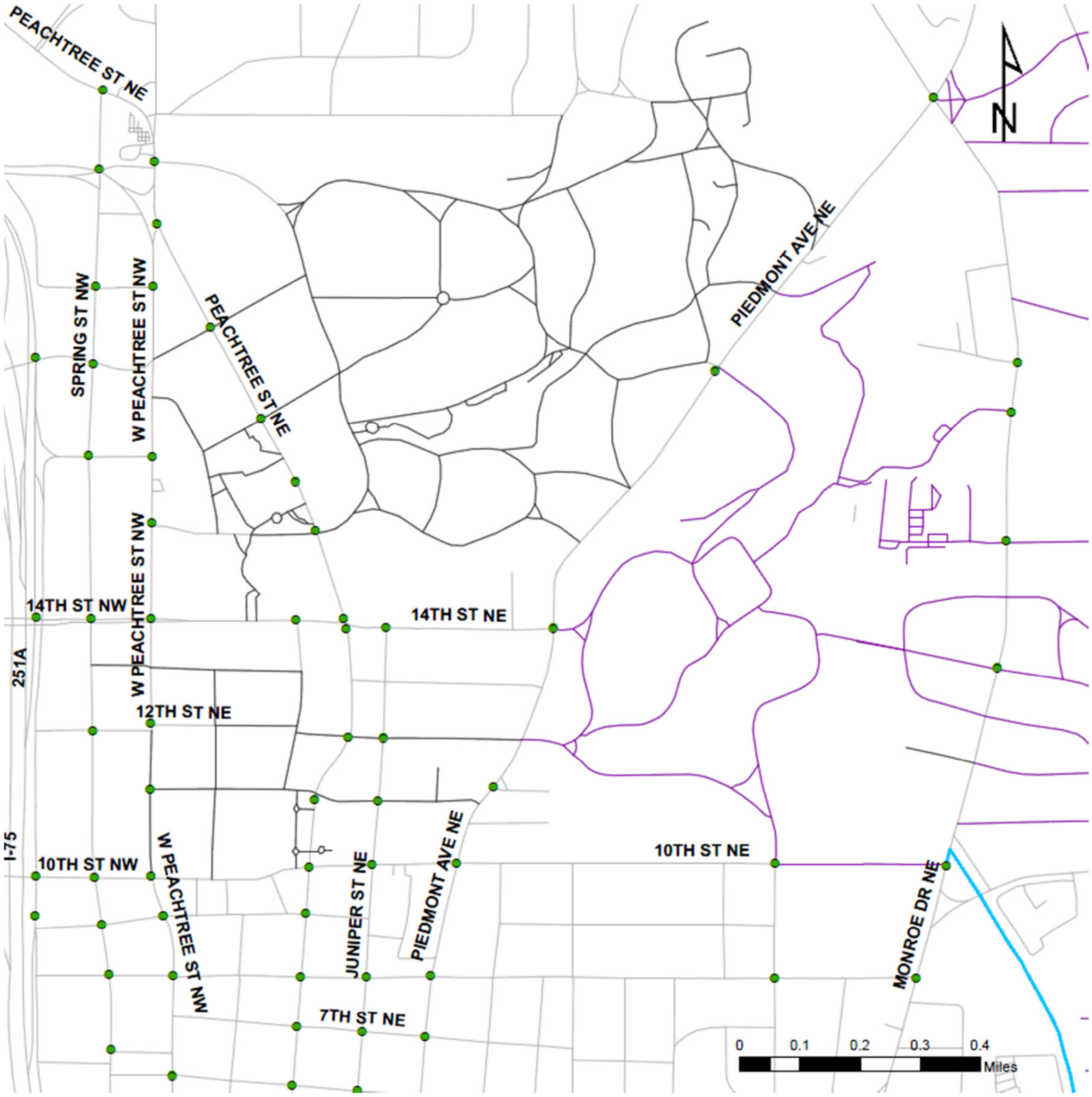


Figure 14: Eastside Trail Bikeshed with LTS 1 and LTS 2 Facilities and Unsignalized Intersection Crossing LTS 1 and LTS 2 Only



Eastside Trail

Eastside Trail Bikeshed LTS 1 & 2

Excluded

Bikeshed

Roadway

Figure 15: Closer View I of the Eastside Trail Bikeshed with Unsignalized Intersection Crossing LTS 1 and LTS 2 Only

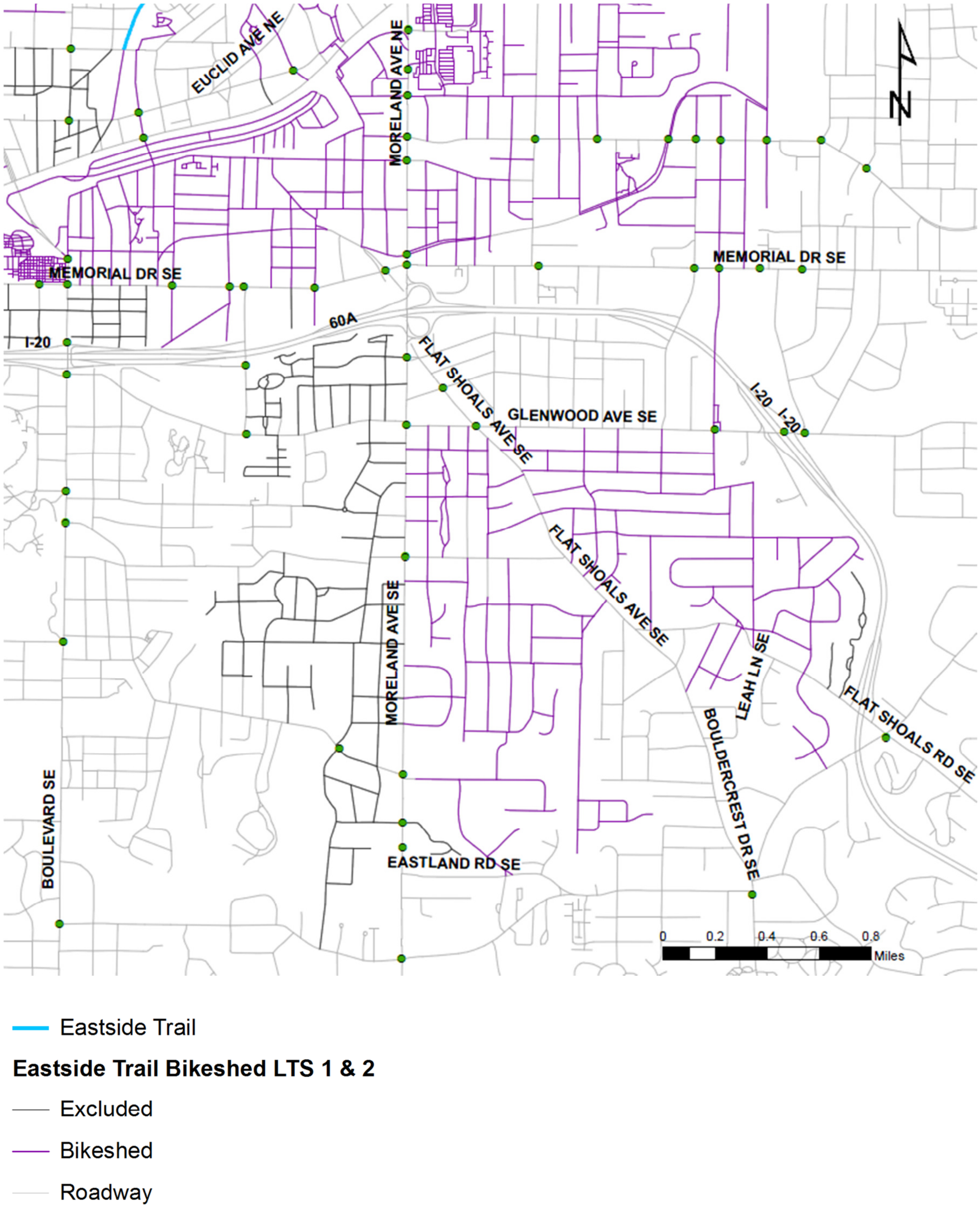


Figure 16: Closer View II of the Eastside Trail Bikeshed with Unsignalized Intersection Crossing LTS 1 and LTS 2 Only

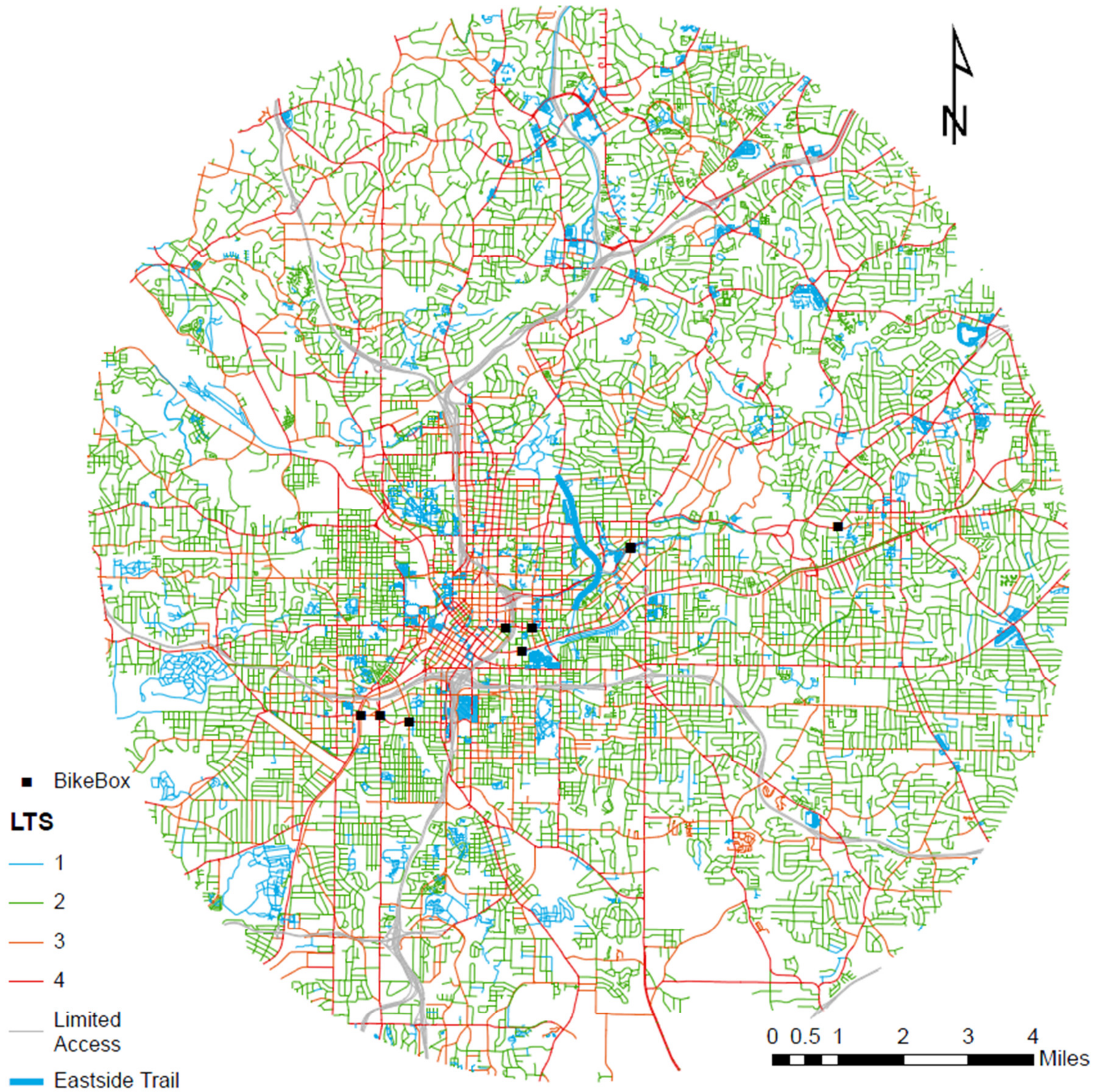


Figure 17: Bike Boxes in the Case Study Area

Conventional bicycle lanes, buffered bicycle lanes, and protected cycle tracks without left-turn facilities (a bike box or two-stage turn queue box) were not penalized in this analysis. See Figure 17 for the location of bike boxes in the study area. There were no two-stage turn queue boxes in the study area. While, left-turn LTS criteria was not included in this analysis, the presence or lack of bike boxes will be an important consideration in future research especially research focused on route analysis.

CHAPTER 5

FUTURE RESEARCH

5.1 Criteria for Links

Link criteria that should be considered include pavement markings and signage, traffic calming features, slope, bicycle lane blockage and bicycle boulevards.

5.1.1 Pavement Markings and Signage

Pavement markings and signage were not considered as criteria for determining LTS in this analysis due to a lack of research on their impact on bicyclist perceived comfort on a particular facility. However, Winters previously mentioned survey of Metro Vancouver residents found that participants preferred residential facilities that were marked as a bicycle route, which has some potential bearing for bicycle boulevards with route signage [10].

5.1.2 Traffic Calming

Traffic calming features were also not considered, however, Winters' survey of Metro Vancouver current and potential bicyclists found that participants preferred roads with traffic calming features over those without [10].

5.1.3 Slope

Winters' survey of Metro Vancouver current and potential bicyclists found that steep grades were a deterrent to riding, however, an exact gradient was not specified [14]. Survey participants showed virtually no negative response to routes with a few small hills, however, they expressed that a route with long steep sections was a significant deterrent to riding [14]. Slope has the potential to reduce the attraction of a bicycle route and should be analyzed before a route is installed on the roadway, however, this analysis could not include slope at the link level since current and potential bicyclists did not show a negative response to short segments with a higher slope.

Thirty percent of participants in a survey in Portland, OR who wanted to travel more by bicycle listed “too many hills” as an environmental barrier which kept them from bicycling more, while 56% ranked the top barrier as “too much traffic” [15]. See the literature review section for more information about slope and why this variable was not used for this analysis.

5.1.4 Bicycle Lane Blockage

Bicycle lanes that are blocked by parked cars or trucks unloading, force bicyclists to swerve into the travel lane. Bicycle lane blockage occurs more often in commercial areas where unloading and loading of goods occurs. However, there is not a readably available data source with information on the frequency of bicycle lane blockage by motor vehicles. Mekuria et al. included bicycle lane blockage as a variable when calculating MTI LTS and cited Dutch design standards as an inspiration. The Dutch recognize that locations with on street parking and high turnover, cars parking and leaving parking spaces frequently, and high occupancy, potentially resulting in double parking, presents a higher potential of bicycle lane blockage by motor vehicles. However, data on turnover and parking occupancy is not readably available so the MTI LTS study classified commercial blocks as having frequent blockage and residential blocks as having infrequent blockage. It was decided that bicycle lane blockage would not be included in this study due to the lack of research on the influence of bicycle lane blockage on perceived level of comfort and lack of research on the use of commercial or residential land use as a proxy for turnover and parking occupancy.

5.1.5 Bicycle Boulevards

The role of bicycle boulevards in the bicycle network should also be analyzed further. Broach et al found that bicyclists placed great value on bicycle boulevards. However, bicycle boulevards are a new treatment in the U.S. and little research has been conducted on the facility type. Bicycle boulevards can potentially make local roads less stressful by reducing motor vehicle speeds and by redirecting motor vehicles away from local roadways toward collector and arterial roadways. Bicycle boulevards are also cheaper to construct than separated paths [35].

5.1.6 Other Criteria Not Used

Loading zones, transit stops, driveways, and green pavement markings along protected cycle tracks were excluded from this analysis due to lack of research, however, these are important design elements and should be incorporated in a level of traffic stress analysis in the future.

5.2 Criteria for Signalized Intersections

Signalized intersection criteria that should be considered include signalized separated turning movements and design of the vehicle entry point.

5.2.1 Signalized Separated Turning Movements

Bicycle signals may be installed at signalized intersections to reduce conflict between motor vehicles and bicycles by creating separate signal phasing for motor vehicle and bicycle movements. Limited research has been conducted on bicycle traffic signals, however, recent research found that 92% of bicyclists surveyed at an intersection with separated bicycle signal phases agreed that they felt “safe” when traveling through the intersection [56]. Increased perception of safety may be due to increased expectancy, in which both bicyclists and motorists clearly understand how they should comply with the traffic and bicycle signals. Separated signal phasing should remove all conflicts as long as all users comply [56]. A video surveillance study in Chicago found that compliance rates for bicyclists and motor vehicles was generally high, with 77 – 93% of bicyclists complying at the five intersections with bicycle traffic signals studied [56]. Little research has been conducted on the effect of bicycle specific signals on perceived LTS, so this intersection design was not included in this analysis.

Bicycle specific signals are currently considered experimental in the 2009 MUTCD, however, they may be included in the 2016 MUTCD.

While there is not significant research on bicycle signalized intersections that separate bicycle and motor vehicle traffic from legally conflicting, initial research has shown that a higher percentage of bicyclists perceive such intersection designs as safer than other intersection designs for protected bicycle facilities [56].

5.2.2 The vehicle entry point

The vehicle entry point for through bicycle lanes in turning zones and mixing zones is a high-conflict area. The vehicle entry point is marked by dotted or dashed lines which signify the merge area and are required to begin a minimum of 50 feet before the intersection [64]. Figure 18 below illustrates vehicle entry point markings for a through bicycle lane. The 2nd Edition of the NACTO Bikeway Design Guide recommends that the dotted lines begin 100 feet before the intersection if the vehicle entry point is located along a high speed or volume roadway. The vehicle entry point serves to alert motorists to the need to yield to merging bicycle traffic and marks the appropriate location for motorists to safely merge across the bicycle lane into the turn lane [52]. There are various designs for vehicle entry points, however, little research has been conducted on the most effective design. Initial research has found that a mixing zone with yield pavement markings for motor vehicles has the most effective motor vehicle compliance in yielding to bicycle traffic [56]. A research study also found that clearly marking the vehicle entry point is important to reducing motor vehicles turning left or right from the wrong lane instead of using the mixing lane or turning zone next to the through bicycle lane [56]. However, facility design for the vehicle entry point was not included in this analysis due to lack of research.

Figure 18: Vehicle Entry Point Markings at a Through Bicycle Lane [52].

5.3 Criteria for Unsignalized Intersections: Bicycle Through Movement at Unsignalized Intersections with and without a Median Refuge Island

A criteria table for unsignalized crossing was discussed in the Chapter 3 Methodology and was applied in the case study area for LTS 1 and LTS 2 facilities when analyzing the bikeshed of the Atlanta BeltLine Eastside Trail. However, future research should consider applying expanded criteria for unsignalized crossings with consideration for traffic volume and the presence of a median refuge island on the cross street. Median refuge islands expand the number of lanes tolerable for each LTS since they allow bicyclists to consider only one direction of traffic at a time and allow a bicyclist to rest mid-crossing while they wait for an acceptable gap in traffic to complete the unsignalized crossing. The 2014 NACTO Urban Bikeway Design Guide recommends a minimum width of six feet for a median refuge island and desirable width of 10 feet [52]. See Figure 19 for an example of median refuge island from the 2014 NACTO Urban Bikeway Design Guide.

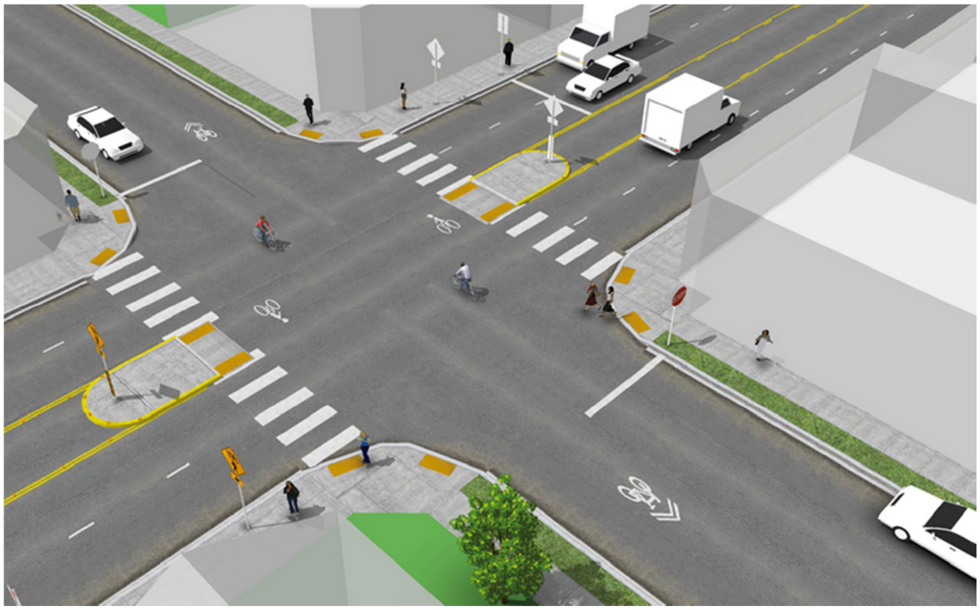


Figure 19: Example of a Median Refuge Island at an Unsignalized Crossing [52]

Table 20: Criteria for Unsignalized Intersection Crossing without a Median Refuge Island

Criteria for Unsignalized Crossings without a Median Refuge Island				
		Street Width		
		≤ 3 lanes	4 - 5 lanes	≥ 6 lanes
Speed Limit	≤ 25 mph	LTS 1	LTS 2	LTS 4
	30 mph	LTS 2	LTS 2	LTS 4
	35 mph	LTS 2	LTS 3	LTS 4
	≥ 40 mph	LTS 3	LTS 4	LTS 4
Note: number of lanes refers to entire street				

Table 21: Criteria for Unsignalized Intersection Crossing with a Median Refuge Island

Criteria for Unsignalized Crossings with a Median Refuge Island				
		Street Width		
		≤ 3 lanes	4 - 5 lanes	≥ 6 lanes
Speed Limit	≤ 25 mph	LTS 1	LTS 2	LTS 2
	30 mph	LTS 1	LTS 2	LTS 3
	35 mph	LTS 2	LTS 2	LTS 4
	≥ 40 mph	LTS 3	LTS 3	LTS 4
Note: number of lanes refers to entire street				

5.4 Validating LTS Typology: Current versus Potential Bicyclist Population

Most research on bicycling has focused on those who already bicycle as this population is easily accessibly especially for surveys that use convenience sampling for recruitment via existing online or offline bicycle groups. Additional research needs to be conducted to reach the population who bicycles infrequently or who do not currently bicycle at all but are interested.

5.5 Validating LTS Quality of Service Tool Criteria: Stated versus Actual Preference

Additional research needs to be conducted to gather data on bicyclist stated preference and actual preference. Stated preference can be studied through surveys gathering information on preferred facility type through hypothetical scenarios via photograph or video. Gathering data on stated preferred facility designs is important because studies have shown that most U.S. cities lack the infrastructure that people state they prefer to bicycle on [10]. While stated preference can introduce some bias, as people’s actual behavior may not result in them choosing the options that they had stated preference surveys will remain important while innovative bicycle facilities remain limited in many U.S. cities.

Studying revealed preference by comparing actual bicycle routes versus shortest routes offers many opportunities to learn more about built environment factors which influence route choice. Winters et al have looked at shortest route versus actual route of bicyclists [33] [34]. Other research has focused on comparing shortest route and actual route and analyzing the built environment factors that influence route choice [34] [67] [36] [35] [68] [69].

CHAPTER 6

CONCLUSION

Most U.S. cities lack connected bicycle networks that meet the stress tolerance of the majority of current and potential bicyclist. The lack of roadways and bikeways that are perceived as comfortable or low stress may be one reason that the bicycling mode share in the U.S. is much lower than in many European cities. The objective of this study was to refine and apply a refined version of the LTS quality of service tool. A quality of service tool like LTS provides a method for categorizing roadways and bikeways based on their perceived level of stress. This research refined the LTS tool introduced by the MTI, however, the current and potential bicyclist typology and the design and traffic criteria used in the LTS quality of service tool should be modified based on the results of future research.

The refined LTS tool used in this thesis was applied in a case study area, a six-mile buffer around the Atlanta BeltLine Eastside Trail in Atlanta, Georgia. Approximately 15 % of the links in the study area were categorized as LTS 1 and 54% percent of the links were categorized as LTS 2. Approximately 64% of the roadway and bikeway network was categorized as low stress (LTS 1 and LTS 2) and would not exceed the stress tolerances of the majority of the population. However, bikeshed analysis which measured the distance that can be traveled from the Eastside Trail outward found that these low stress facilities are not well connected.

Previous research has shown that bicyclists prefer to ride on bicycle routes and local roads and prefer to avoid arterials [33], while motor vehicle drivers prefer highways and arterials and tend to avoid local roads. The LTS quality of service tool categorizes local and collector roads with low posted speed limits and traffic volumes as lower stress and more suitable to the majority of current and potential bicyclists. By orienting the bicycle network toward low stress bikeways and roadways the LTS quality of service tool avoids trying to place bicycle facilities on arterials and other roadways with high traffic volume, posted speed, and number of through lanes, which are preferred for motor vehicle traffic. The 2010 HCM recognizes that accommodating the needs of one mode may have a negative impact on another mode which the methodology behind the LTS quality of service tool takes into consideration. However, by orienting the bicycle network toward low stress roadways and bikeways the network is more likely to be disconnected.

Future research which includes LTS will likely analyze connectivity and routes. The roadway and bikeway database used in this research includes direction information for the roadway network, however, the bikeway network is more simplified. This means that a link with a conventional bicycle lane in one direction and a shared travel lane in the other direction will be categorized only by the bicycle lane. Simplifying the roadway and bikeway network assists in creating maps which can be easily read. However, the roadway and bikeway network should be developed in the future to include directionality. While the simplified roadway and bikeway LTS presented in this thesis were beneficial for visual presentation, this method created some areas of concern. The primary issues were: roadway links with a bicycle facility in one direction, but not the other resulting in a lower LTS categorization, intersection approaches where the bicycle facility was dropped in one direction, but not the other resulting in a higher LTS categorization for the link, roadways where bicycling is restricted due to streetcar rails in one direction, but not the other resulting in an LTS categorization in a restricted access area, and on street parking located by a bicycle facility in one direction by not the other resulting in a lower LTS categorization.

Significant research needs to be conducted to refine the LTS quality of service tool including; validating the four types of bicyclists, refining the traffic and facility characteristics which are used to calculate LTS level for a link, developing stronger intersection LTS criteria, and creating a more robust bikeway and roadway database that includes direction specific LTS data. While, additional work is needed on the LTS tool, this tool holds promise since it includes consideration of the stress tolerances for the entire population, not just current bicyclists.

APPENDIX A MODIFIED LTS CRITERIA TABLES

The following criteria tables were used for roadways, which lacked data on AADT, posted speed and FHWA based functional class. Approximately 654 miles out of a total of 2,267 miles utilized this alternative LTS criteria, which is based on NAVTEQ roadway data. While there are 1,613 miles of roadway with RC_ROUTES_ARC data. AADT was completely omitted in these tables since there was no alternative data that could be used. However, the NAVTEQ has its own functional class which is more simplified than the functional classification system used in the main LTS criteria tables. The functional classes used by NAVTEQ are listed below:

Table 22: Functional Class Descriptions for NAVTEQ Streets 2014 [66]

Functional Class Level	Description
1	Roads that allow for high volume, maximum speed traffic movement between and through major metropolitan areas with very few, if any, speed changes and usually access controlled.
2	Roads used to channel traffic to functional class 1 roads for travel between and through cities in the shortest amount of time. Few, if any speed changes that allow for high volume, high speed traffic movement.
3	Roads which interconnect functional class 2 roads and provide a high volume of traffic movement at a lower level of mobility than functional class 2 roads.
4	Roads which provide for a high volume of traffic movement at moderate speeds between neighbhoorhodds and connect to higher functional class roads to collect and distribute traffic between neighborhoods.
5	Roads whose volume and traffic movement are below the level of any functional class.

NAVTEQ also had information on speed simplified to categories of posted speed limit instead of specific posted speed limits. However, these speed categories fit within the LTS categories which were used in the main LTS criteria tables with the exception of LTS 1 speed category which was 0 to 20 mph for the NAVTEQ only links, but was 0 to 25 mph for the main LTS criteria tables.

Tables 23 through 27 below present the alternative LTS criteria tables.

Table 23: NAVTEQ Criteria for Conventional Bicycle Lanes Not Alongside a Parking Lane

Alternative Criteria for Bike Lanes Not Alongside a Parking Lane				
	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (through lanes)	2 - 3	(no effect)	≤ 4	(no effect)
Traffic Volume (AADT)	Data not available	Data not available	Data not available	Data not available
Functional Class Category	5	4	3	≤ 2
Speed Category	0 - 20 mph	21 - 30 mph	31 - 40 mph	> 40 mph

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

Table 24: NAVTEQ Criteria for Conventional Bicycle Lanes Alongside a Parking Lane

Alternative Criteria for Bike Lanes Alongside a Parking Lane				
	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (through lanes)	2 - 3	(no effect)	≤ 4	(no effect)
Traffic Volume (AADT)	Data not available	Data not available	Data not available	Data not available
Functional Class Category	5	4	(no effect)	≤ 3
Speed Category	0 - 20 mph	21 - 30 mph	31 - 40 mph	> 40 mph

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

Table 25: NAVTEQ Criteria for Buffered Bicycle Lanes Not Alongside a Parking Lane

Alternative Criteria for Buffered Bike Lanes Not Alongside a Parking Lane				
	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (through lanes)	2 - 3	(no effect)	≤ 4	(no effect)
Traffic Volume (AADT)	Data not available	Data not available	Data not available	Data not available
Functional Class Category	5 or 4	(no effect)	3	≤ 2
Speed Category	0 - 20 mph	21 - 30 mph	31 - 40 mph	> 40 mph

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

Table 26: NAVTEQ Criteria for Buffered Bicycle Lanes Alongside a Parking Lane

Alternative Criteria for Buffered Bike Lanes Alongside a Parking Lane				
	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (through lanes)	2 - 3	(no effect)	≤ 4	(no effect)
Traffic Volume (AADT)	Data not available	Data not available	Data not available	Data not available
Functional Class Category	5	4	3	≤ 2
Speed Category	0 - 20 mph	21 - 30 mph	31 - 40 mph	> 40 mph

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

Table 27: NAVTEQ Criteria for Shared Travel Lanes

Alternative Criteria for Shared Travel Lanes				
	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (through lanes)	2 - 3	(no effect)	≤ 4	(no effect)
Traffic Volume (AADT)	Data not available	Data not available	Data not available	Data not available
Functional Class Category	5	(no effect)	4	≤ 3
Speed Category	0 - 20 mph	21 - 30 mph	31 - 40 mph	> 40 mph

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

APPENDIX B

USDOT FHWA HIGHWAY FUNCTIONAL CLASSIFICATION

Table 28: USDOT FHWA Highway Functional Class I

Table 3-5: VMT and Mileage Guidelines by Functional Classifications - Arterials

	Arterials			
	Interstate	Other Freeways & Expressway	Other Principal Arterial	Minor Arterial
Typical Characteristics				
Lane Width	12 feet	11 - 12 feet	11 - 12 feet	10 feet - 12 feet
Inside Shoulder Width	4 feet - 12 feet	0 feet - 6 feet	0 feet	0 feet
Outside Shoulder Width	10 feet - 12 feet	8 feet - 12 feet	8 feet - 12 feet	4 feet - 8 feet
AADT[1] (Rural)	12,000 - 34,000	4,000 - 18,500[2]	2,000 - 8,500[2]	1,500 - 6,000
AADT[1] (Urban)	35,000 - 129,000	13,000 - 55,000[2]	7,000 – 27,000[2]	3,000 - 14,000
Divided/Undivided	Divided	Undivided/Divided	Undivided/Divided	Undivided
Access	Fully Controlled	Partially/Fully Controlled	Partially/Uncontrolled	Uncontrolled
Mileage/VMT Extent (Percentage Ranges)[1]				
Rural System				
Mileage Extent for Rural States[2]	1% - 3%	0% - 2%	2% - 6%	2% - 6%
Mileage Extent for Urban States	1% - 2%	0% - 2%	2% - 5%	3% - 7%
Mileage Extent for All States	1% - 2%	0% - 2%	2% - 6%	3% - 7%
VMT Extent for Rural States[2]	18% - 38%	0% - 7%	15% - 31%	9% - 20%
VMT Extent for Urban States	18% - 34%	0% - 8%	12% - 29%	12% - 19%
VMT Extent for All States	20% - 38%	0% - 8%	14% - 30%	11% - 20%
Urban System				
Mileage Extent for Rural States[2]	1% - 3%	0% - 2%	4% - 9%	7% - 14%
Mileage Extent for Urban States	1% - 2%	0% - 2%	4% - 5%	7% - 12%
Mileage Extent for All States	1% - 3%	0% - 2%	4% - 5%	7% - 14%
VMT Extent for Rural States[2]	17% - 31%	0% - 12%	16% - 33%	14% - 27%
VMT Extent for Urban States	17% - 30%	3% - 18%	17% - 29%	15% - 22%
VMT Extent for All States	17% - 31%	0% - 17%	16% - 31%	14% - 25%
Qualitative Description (Urban)	• Serve major activity centers, highest traffic volume corridors, and longest trip demands • Carry high proportion of total urban travel on minimum of mileage • Interconnect and provide continuity for major rural corridors to accommodate trips entering and leaving urban area and movements through the urban area • Serve demand for intra-area travel between the central business district and outlying residential areas			• Interconnect with and augment the principal arterials • Serve trips of moderate length at a somewhat lower level of travel mobility than principal arterials • Distribute traffic to smaller geographic areas than those served by principal arterials • Provide more land access than principal arterials without penetrating identifiable neighborhoods • Provide urban connections for rural collectors
Qualitative Description (Rural)	• Serve corridor movements having trip length and travel density characteristics indicative of substantial statewide or interstate travel • Serve all or nearly all urbanized areas and a large majority of urban clusters areas with 25,000 and over population • Provide an integrated network of continuous routes without stub connections (dead ends)			• Link cities and larger towns (and other major destinations such as resorts capable of attracting travel over long distances) and form an integrated network providing interstate and inter-county service • Spaced at intervals, consistent with population density, so that all developed areas within the State are within a reasonable distance of an arterial roadway Provide service to corridors with trip lengths and travel density greater than those served by rural collectors and local roads and with relatively high travel speeds and minimum interference to through movement

1- *Ranges in this table are derived from 2011 HPMS data.*

2- *For this table, Rural States are defined as those with a maximum of 75 percent of their population in urban centers.*

Table 29: USDOT FHWA Highway Functional Class II

Table 3-6: VMT and Mileage Guidelines by Functional Classifications – Collectors and Locals

	Collectors		Local
	Major Collector[2]	Minor Collector[2]	
Typical Characteristics			
Lane Width	10 feet - 12 feet	**10 - 11 feet**	8 feet - 10 feet
Inside Shoulder Width	0 feet	0 feet	0 feet
Outside Shoulder Width	1 feet - 6 feet	**1 feet - 4 feet**	0 feet - 2 feet
AADT[1] (Rural)	300 - 2,600	150 - 1,110	15 - 400
AADT[1] (Urban)	1,100 - 6,300[2]		80 - 700
Divided/Undivided	Undivided	Undivided	Undivided
Access	Uncontrolled	Uncontrolled	Uncontrolled
Mileage/VMT Extent (Percentage Ranges)[1]			
Rural System			
Mileage Extent for Rural States[3]	8% - 19%	3% - 15%	62% - 74%
Mileage Extent for Urban States	10% - 17%	5% - 13%	66% - 74%
Mileage Extent for All States	9% - 19%	4% - 15%	64% - 75%
VMT Extent for Rural States[3]	10% - 23%	1% - 8%	8% - 23%
VMT Extent for Urban States	12% - 24%	3% - 10%	7% - 20%
VMT Extent for All States	12% - 23%	2% - 9%	8% - 23%
Urban System			
Mileage Extent for Rural States[3]	3% - 16%	3% - 16%[2]	62% - 74%
Mileage Extent for Urban States	7% - 13%	7% - 13%[2]	67% - 76%
Mileage Extent for All States	7% - 15%	7% - 15%[2]	63% - 75%
VMT Extent for Rural States[3]	2% - 13%	2% - 12%[2]	9% - 25%
VMT Extent for Urban States	7% - 13%	7% - 13%[2]	6% - 24%
VMT Extent for All States	5% - 13%	5% - 13%[2]	6% - 25%
Qualitative Description (Urban)	• Serve both land access and traffic circulation in higher density residential, and commercial/industrial areas • Penetrate residential neighborhoods, often for significant distances • Distribute and channel trips between local streets and arterials, usually over a distance of greater than three-quarters of a mile	• Serve both land access and traffic circulation in lower density residential, and commercial/industrial areas • Penetrate residential neighborhoods, often only for a short distance • Distribute and channel trips between local streets and arterials, usually over a distance of less than three-quarters of a mile	• Provide direct access to adjacent land • Provide access to higher systems • Carry no through traffic movement
Qualitative Description (Rural)	• Provide service to any county seat not on an arterial route, to the larger towns not directly served by the higher systems, and to other traffic generators of equivalent intra-county importance such as consolidated schools, shipping points, county parks, important mining and agricultural areas • Link these places with nearby larger towns and cities or with arterial routes • Serve the most important intra-county travel corridors	• Be spaced at intervals, consistent with population density, to collect traffic from local roads and bring all developed areas within reasonable distance of a minor collector • Provide service to smaller communities not served by a higher class facility • Link locally important traffic generators with their rural hinterlands	• Serve primarily to provide access to adjacent land • Provide service to travel over short distances as compared to higher classification categories • Constitute the mileage not classified as part of the arterial and collectors systems

1- *Ranges in this table are derived from 2011 HPMS data.*

2- *Information for Urban Major and Minor Collectors is approximate, based on a small number of States reporting.*

3- *For this table, Rural States are defined as those with a maximum of 75 percent of their population in urban centers.*

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